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The circulation and fluxes from the Arctic into the North Atlantic Ocean 1979-2002 model results

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MONTEREY, CALIFORNIA

THESIS

THE CIRCULATION AND FLUXES FROM THE ARCTIC INTO THE NORTH ATLANTIC OCEAN: 1979-2002 MODEL RESULTS

by

Catherine E. Williams

September 2004

Thesis Advisor: Wieslaw Maslowski
Second Reader: Albert Semtner

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The recent decreasing trend of sea ice cover in the Arctic region and its projected future reduction has direct implications for the global thermohaline circulation and the U.S. Navy. This thesis provides a qualitative and quantitative analysis of the freshwater export from the Arctic Ocean through the Canadian Arctic Archipelago (CAA) and the Fram Strait into the deep-water formation region of the Labrador Sea, using model data from 1979 to 2002. The results of this thesis directly aid the Navy in preparing personnel, ships, and weapons systems to operate efficiently in a possible ice-free Arctic.

A coupled ice-ocean model of the pan-Arctic region at a 1/12-degree and 45-level grid resolution was used to produce data over a 24-year time period. The 24-year averaged annual velocity, temperature, and salinity profiles were compared for each of the analyzed stations. Additionally, 24-year mean monthly volume and freshwater flux time series plots and annual cycle plots were also produced to analyze the region's interannual variability from 1979 to 2002.

The results show that the Canadian Arctic Archipelago is the major contributor of freshwater to the Labrador Sea. The CAA is a direct pathway for increased freshwater export from the Arctic into the sub-arctic seas where North Atlantic Deep Water(NADW)forms. The increased freshwater flux through the CAA, found in this study, supports the earlier reports on the freshening of NADW and a possibility of reduction in the meridional overturning rate in the North Atlantic. An increase in freshwater export from the Arctic is a good indicator of increasing sea ice reduction. The predicted opening of the Arctic to commercial and military vessels poses a direct threat to U.S. economical and strategic interests in the Arctic region. This thesis supports the U.S. Navy's ability to operate in a possibly ice-free Arctic.

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I. INTRODUCTION

A. IMPORTANCE OF THE ARCTIC REGION

The Arctic region remains one of the few understudied regions of the world due to the limited access to this year-around ice-covered region restricting the amount of data collected. Yet, the recent melting of sea-ice has generated more interest and allowed more field experiments to be conducted. Research efforts have been aided by advancements in communications, transportation, and scientific instrumentation, allowing scientists to gain more access to a once secluded region. Yet, this “conventional” approach is somewhat limited, expensive and still heavily dependent upon the environmental conditions. This is why the advancements in Arctic atmospheric, ocean and sea-ice models are so important to the continued investigation of the Arctic environment. Models can provide information, which is otherwise unavailable, or if it is, at a much more cost-effective price compared to conventional methods. However, models have their own limitations and weaknesses so it is important to continue with both approaches. The combination of field and model data will only advance research in the Arctic, and enable scientists to move further in understanding the Arctic Ocean dynamics and its importance on the global climate.

The global thermohaline circulation or “conveyor belt” theory (Broecker, 1991) describes the redistribution and balance of heat throughout the world ocean (Figure 1.1). It is influenced by many different water masses but some of the most crucial in driving the global circulation are formed in the Arctic and sub-arctic region. The Arctic

Ocean with its marginal seas is responsible for the formation of dense bottom and intermediate waters, some of which flow south out of the Greenland, Iceland, and Labrador Seas into the North Atlantic (Aagaard, 1985). The dense, cold, salty waters produced in the northern North Atlantic travel south cooling the warmer waters at lower latitudes. The deep waters originating from the pan-Arctic region are also important in providing more saline water to the Pacific and helping to restore its salinity deficit (Wijffels, 1992).

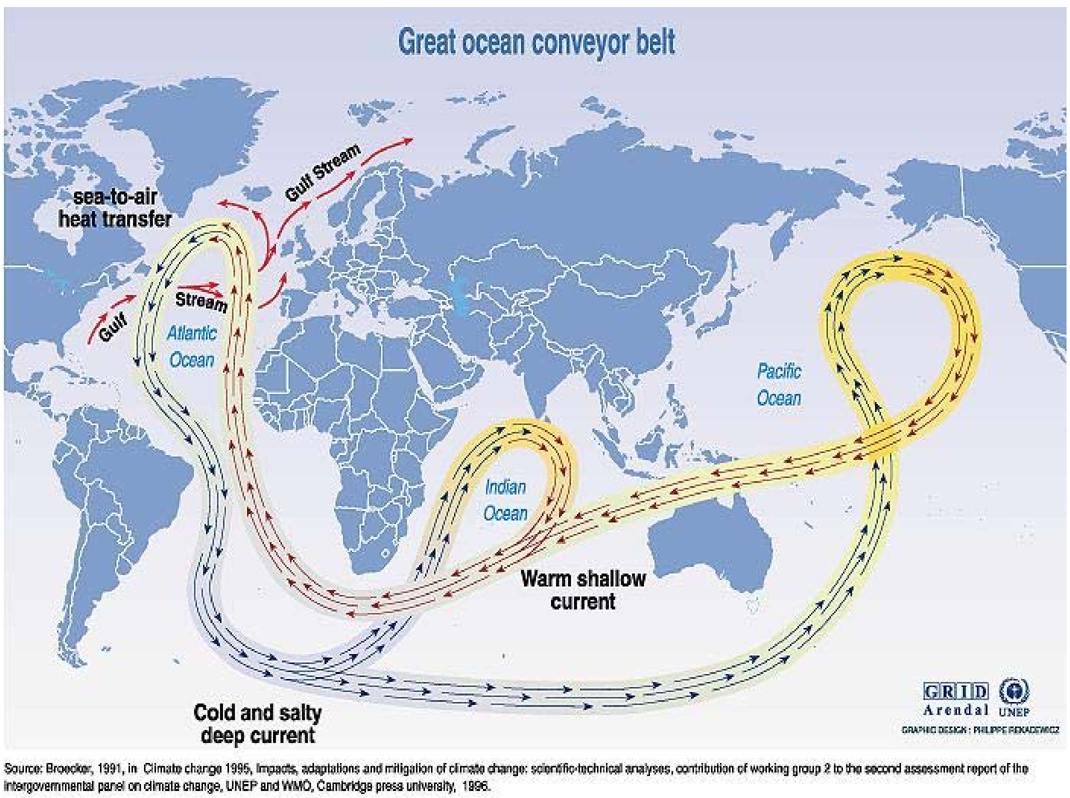

Figure 1.1 Great ocean conveyor belt-shows the path of the global thermohaline circulation. Formation of the NADW in the northern North Atlantic drives the circulation.
From http://www.grida.no/climate/vital/32.htm (05/20/2004)

The rate and variability of these intermediate and deep-water masses formation is not fully understood, but it is well known that their formation is due to open-ocean convection. The open-ocean convection occurs when atmospheric cooling causes warm and saline surface waters to become dense and descend down the water column. Another method of deep-water mass formation is through sea ice formation on the continental shelves. This saline water gradually descends down the slopes and becomes mixed with the deep basin water.

However, densities of surface waters are sensitive to salinity changes and therefore larger amounts of fresher water at the surface could slow down or completely stop convection (Lazier, 1980). The increase in sea-ice melt in the Arctic results in larger amounts of freshwater export to the sub-arctic seas. Such changes in the pan-Arctic environment could have dramatic ramifications not only for the Arctic but also for global climate as well (Dickson, 1999).

It is well known that the atmosphere, ocean currents, sea ice, and land runoff interact together to produce the world's climate. Therefore, it is important to consider all these factors to understand any changes that are taking place. The atmospheric regime over the Arctic can be in part described by the Arctic Oscillation (AO), and/or with the North Atlantic Oscillation (NAO), that oscillates naturally from a positive to negative state (Thompson and Wallace, 1998). Negative AO/NAOs are associated with colder atmospheric temperatures and higher pressure driving anti-cyclonic ocean currents around the Arctic. During a negative NAO, a build up of freshwater in the western Arctic occurs along with an increase in sea ice thickness.

Additionally, there is a reduction in freshwater export from the Fram Strait, which leads to an increase of convection in the Greenland Sea (Proshutinsky, et al. 2002). During the positive AO/NAO, a shift in ocean circulation occurs with warmer waters from the North Atlantic entering the Western Arctic Ocean. The oceanic shift is associated with warmer air temperatures and an increased sea ice melt. These changes result in an increased freshwater outflow from the Arctic to the sub-Arctic seas (Proshutinsky, et al. 2002). Sea level pressure (SLP) over the Fram Strait is also highly correlated with positive NAOs according to Kwok and Rothrock (1999) who found that from 1988 until the late 1990s lower SLP over the Arctic coincided with more prevalent positive NAO phases. This agrees with Proshutinsky et al. (2002), who noted less intense Arctic highs, characteristic of negative NAO, and longer lasting summer cyclones, associated with positive NAO, between 1989 and 1997. During this time there was a decrease in the freshwater content of the Canadian Basin, due to the release of the accumulated fresh surface waters, out of the Arctic (McLaughlin, et al. 2002). The increase in freshwater discharge from the Arctic Ocean was seen further downstream in the Labrador Sea in the early 1990s when the Labrador Sea Water was fresher and ,colder than any other deep water measurements taken (Dickson et al, 2002).

Global warming has been hypothesized as one of the causes for the increase in sea ice melt and freshwater content in the Arctic (Vinje, 2001), which has coincided with more prevalent positive NAO shifts, over the past several decades (Dickson, 2002). However, Vinje (2001) warns that before any conclusions can be made extensive

analyses of data collected over 30 years or more should be made to rule out the possibility of these changes merely being natural occurrences. However, the limited long-term data sets in the Arctic are not sufficient to determine if the changes seen in the last four decades are anthropogenic or part of the natural fluctuations (Broecker, 1991). Based on paleo-records, Darby et al. (2001) also warn against making the conclusion that the greenhouse effect is the cause of recent increases of surface air temperatures and sea ice melt in the Arctic. These authors note that more research is needed, to determine if arctic climate regimes based on the AO could naturally oscillate on longer time scales associated with global climatic variability.

The focus of this research is on the freshwater flux from the Arctic Ocean through the Canadian Arctic Archipelago and via the Fram Strait in to the Labrador Sea. The primary data used for analyses is from the Naval Postgraduate School high resolution coupled ice-ocean model of the Pan-Arctic region from 1979-2002 (Maslowski et. al 2004 and Maslowski and Lipscomb 2003). The amount of freshwater flux from these pathways are compared against each other to determine the total amount of freshwater, which leaves the Arctic Ocean and enters the Labrador Sea. This research also quantifies the export of freshwater through these pathways into the Labrador Sea and analyzes its interannual to decadal variability.

Analysis of the freshwater output from the Arctic entering the Labrador Sea is extremely important in determining what effects the freshwater could have on the North Atlantic Deep Water (NADW). Since, "the Labrador Sea Water directly determines the rate of the main Atlantic gyre circulation," (Dickson et al, 2002). Therefore, if

the amount of freshwater entering the Labrador Sea’s surface water is large enough it could significantly reduce or completely shut down the global thermohaline circulation (Dickson et al., 2002). Changes in the thermohaline circulation in the North Atlantic would mean that the warm water carried by the Gulf Stream will not reach as far north or east in the Atlantic. Therefore, Northern Europe would not experience such mild weather conditions (Aagaard and Carmack, 1994), but might shift to the harsher, colder climate characteristic of Alaska and northern Canada.

B. CANADIAN ARCTIC ARCHIPELAGO AND THE HUDSON BAY

Little is known about the Canadian Arctic Archipelago (CAA), mostly because throughout much of the year it is ice covered and therefore inaccessible to most vessels, excluding icebreakers. However, it is gaining in importance due to reductions of sea-ice extent in the Arctic and the possibility of a Northwest Passage opening by 2050(U.S. Arctic Research Commission, Special Pub. No. 02-1). The international Arctic/Sub arctic Ocean Fluxes (ASOF) program has also been established in part to further research in the CAA.

The Canadian Arctic Archipelago connects the surface waters of the Western Arctic Ocean to the North Atlantic (Melling, 2004) by allowing water from the continental shelves of the Canadian Basin to flow over shallow sills of the Canadian Archipelago and then transit into the northern Baffin Bay (Melling et al., 1984). Most waters entering the Northwestern Archipelago are cold, low salinity surface waters produced from sea ice melt, river runoff, or from low salinity water entering from the Pacific Ocean through the Bering Strait (Melling et al., 1984). These waters

pass from the northwestern Archipelago through several pathways until encountering shallow sills in the Lancaster Sound and Jones Sound before entering into the northern Baffin Bay. Once in the northern Baffin Bay the flow is directed southwards toward the Labrador Sea. Once this flow enters the Labrador Sea the southward flow is called the Labrador Current and is found along the shelf and upper slope of the western side of the Labrador Sea (Cuny et al., 2002). On the eastern side of the Labrador Sea the West Greenland Current (WGC) carries cold and fresh waters north along the continental shelf and slope with the warmer, saltier Irminger Sea water below it. At about 61°N the majority of northward flowing water turns westward due to the Davis Strait and flows south with the Labrador Current (Cuny et al., 2002). Through the use of drifter data, Cuny et al. (2002) showed that the eastern side of the Labrador Sea is warmer, more saline and faster than the western side of the Labrador Sea where the flow is directed southward. This is due mainly to the northward transport of the warm, saline West Greenland Current (WGC) which is cooled by isopycnal mixing with ambient water of the Labrador Sea. Labrador Sea Water (LSW) is believed to form in the Labrador Sea by convection, when cold winds from the north cause the surface waters to become cold enough to sink. The presence of the warmer Irminger Sea Water allows the Labrador Sea to restratify after convection and keeps the Labrador Sea ice-free (Cuny et al. 2002).

Another potentially important freshwater source to the Labrador Sea is also from the CAA but it enters via the Hudson Bay. The Hudson Bay is connected to the CAA by the Foxe/Hecla Strait. This strait acts as the Hudson's only connection to the Arctic Ocean. Therefore, the flow

through Foxe/Hecla is a major contributor to the salinity and temperature properties of the Hudson Bay. The other important freshwater sources to the Hudson Bay come from river runoff. It is important to determine the freshwater flux from the Hudson Bay to the Labrador Sea as it may play a significant role in Labrador Sea Water (LSW) formation.

C. FRAM STRAIT, DENMARK STRAIT, AND CAPE FAREWELL

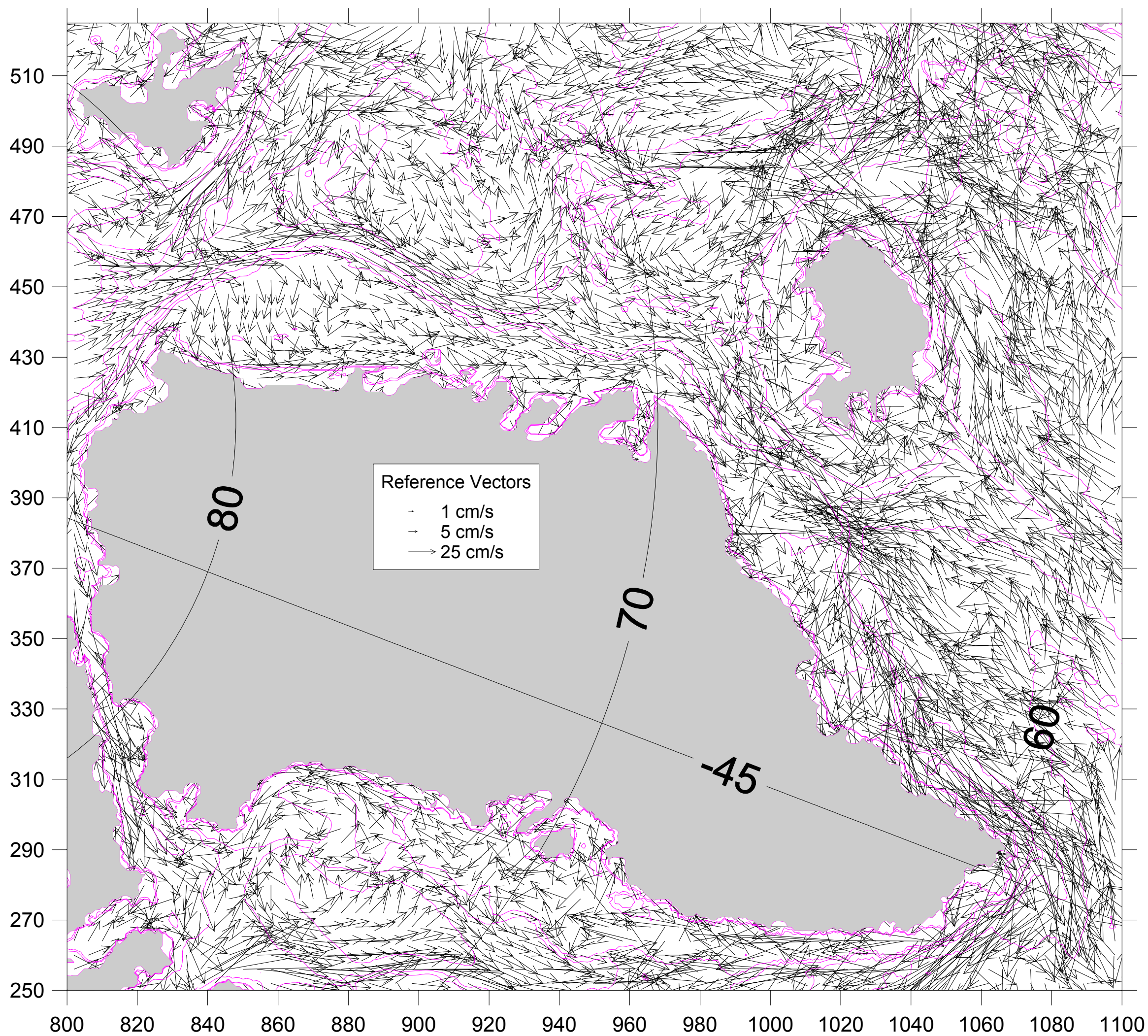

Figure 1.2 24-year average circulation pattern over 100m depth of the Fram and Denmark Straits.

The Fram Strait region lies between the northeast portion of Greenland, and Spitsbergen. It is the major pathway for water and sea ice exiting and entering the Arctic Ocean (Carmack, 2000). The Fram Strait has a distinctive flow regime, which is important to understand in evaluating the volume flux. The general oceanic flow pattern is a northward flow of relatively warm, saline North Atlantic water carried by the West Spitsbergen Current. Then there is a distinct direction change on the western side of the Fram Strait, with the East Greenland Current, carrying relatively cold and fresh surface waters and re-circulated Atlantic water from the Arctic Ocean into the Greenland and Iceland seas. This flow pattern can be seen in Figure 1.3. However, the flow regime is further complicated as some water from the West Spitsbergen Current re-circulates south via several branches to the south and at the Fram Strait (Carmack, 2000). This recirculation must be taken into account when calculating volume fluxes through the Fram Strait.

The Fram Strait is important not only because of its outflow of fresh surface waters but also because of its large ice volume flux, which actually contributes more freshwater than the liquid phase exported through the strait (Aagaard and Carmack, 1989). The sea ice movement is driven by atmospheric forcing (40%) and ocean currents (60%) (Vinje, 2000), therefore climatic changes have important effects upon sea ice motion and ultimately freshwater export rates (Vinje, 2000). Vinje et al.(1998) found that maximum ice velocity occurs in January and February due to an influx of thinner ice forced by greater winter wind forcing moving east from the north of Spitsbergen. Kwok and Rothrock (1999) also found that

atmospheric conditions influence sea ice area fluxes. They concluded that there exists a strong correlation (R=0.86) between the ice area flux and the positive phases of the NAO. The increased prevalence of positive NAO phases over the past several decades corresponds with the author's findings of an 18-year increased trend of ice area flux through the Fram Strait.

The sea ice export through the Fram Strait is important because it is the largest contributor of freshwater to the GIN Sea (Aagaard and Carmack, 1989), which may have a direct impact on the convective gyres of the Greenland and Iceland Seas. This is important because these convective gyres produce the dense source waters, which overflow into the North Atlantic, and drive the global thermohaline circulation (Dickson, 1990). Aagaard and Carmack (1989) and Maslowski (1996) proposed that the fast moving East Greenland Current (EGC) remains relatively isolated and does not mix much with the Greenland and Iceland Seas. However, a small percentage of the upper layers of the EGC do get mixed into the GIN Sea (Aagaard and Carmack, 1989). At low temperatures even slight salinity changes associated with an increased amount of freshwater export from the Arctic Ocean could directly, through the mixing of the boundary currents, alter convection in the GIN Sea (Aagaard and Carmack, 1989). Although, this is not the only possibility to affect convection in the GIN Sea, as a freshwater signal can be brought into the area by currents from the North Atlantic (Maslowski, 1996), it could be an important factor in the modification of the global thermohaline circulation.

This thesis evaluates the liquid freshwater fluxes and ice fluxes through the Fram and Denmark Straits and around the tip of Cape Farewell. The reason for this approach is to follow the freshwater exiting the Arctic Ocean into the North Atlantic and quantify the fresher signal from the Arctic Ocean via the Fram and Denmark Straits into the convective region of the Labrador Sea. Dickson et al. (2002) support the notion that freshwater is transported from the GIN Sea to the Labrador Sea through entrainment and mixing with other local water masses. Evidence of a freshwater signal from the GIN Sea was also found to propagate during the Great Salinity Anomaly into the Labrador Sea and then into the North Atlantic (Dickson et al. 1988). Therefore, the Labrador Sea receives water from the Arctic Ocean via the Fram Strait and the CAA and so it is directly affected by any variability of freshwater export from the Arctic Ocean. The increased freshwater fluxes from the Arctic are hypothesized to hinder deepwater formation in the Labrador Sea and to possibly result over a long-term in a slowdown or collapse of the global thermohaline circulation.

D. NAVY RELEVANCE

The Arctic Ocean has been of interest to the U.S. Navy because of its importance in submarine and anti-submarine warfare, especially during the time of the Cold War. This interest stems from the Arctic’s unique environment for submarine operation, which is unlike any other ocean in the world. The Arctic Ocean’s stratification and its multiyear sea ice cap provide many ‘hiding spots’ for submarines. On the other hand, the positive sound gradient causes upward

refraction of sound waves and traps sound energy in surface ducts, where submarines can detect other submarines' noise. The Arctic Ocean also has relatively low ambient noise levels, especially in the central Arctic, which helps in detection. However, in marginal seas the ambient noise due to ice break-up masks any submarine noise, which makes marginal seas a good hiding place for submarines to linger; although this situation does require very good navigation in order to avoid collisions with the moving ice packs (USARC, No.02-1). The Arctic also is positioned geographically as a perfect place to launch nuclear ballistic missiles to reach almost anywhere in the world (USARC, No.02-1). These are just a few reasons why the Arctic played such an important role in the Cold War.

However, at the end of the Cold War the need for submarine patrols in the Arctic Ocean diminished. Therefore, the Navy has put less emphasis in Arctic research and more on studying littoral areas in support of current Naval missions. Increasingly, over the past several decades the Arctic has shown important changes possibly due to climate change. One such change is the potential opening of waterways, which has significant implications for the U.S. Navy in the upcoming future.

A symposium entitled 'Naval operations in an ice-free Arctic' in April 2001, was held by the Office of Naval Research, the Naval Ice Center, the Oceanographer of the Navy, and the Arctic Research Commission to address the current situation in the Arctic region and to hear predictions from a panel of scientists and naval officers. The conclusions drawn from this conference were based heavily upon evidence from current, observable data and models. One likely scenario will be year round ice-free

conditions in the Sea of Japan and the Sea of Okhotsk, by the year 2050. Additionally, the entire Arctic Russian coast will be ice free in the late summer allowing surface ships access to the Barents, Kara, Laptev, and East Siberian Seas, providing a Northern Sea Route. Also, the Northwest Passage through the Canadian Arctic Archipelago and along the Alaskan coast will likely be open to transit in summer by non-icebreaking ships by 2015. Furthermore, the models, supported by satellite observations, predict that by 2050 the Arctic's summer minimum sea-ice extent will be reduced by 15% of current conditions and the end of summer ice volume will decrease by 40%. Ice will remain year round in the central Arctic, but it will be much thinner.

The opening of the Arctic region to surface ships has significant and immediate implications for the U.S. Navy and the United States as a country. The opening of previously inaccessible sea routes creates a new region of threat, which could prove beneficial to adversaries, thereby posing a threat to national security. The economical impacts of new shipping routes are also very important. In 1998 the sole rights to the Murmansk Shipping Company were sold to the Lukoil, a Russian oil company, which presently has a monopoly upon icebreakers and tankers into that region. This, combined with increased cooperation between the European Union and Russia on possible oil production in the area, should be a major concern for American economical interests in the region.

The opening of a Northwest Passage will undoubtedly increase commercial shipping through this area, including seas to the north of Alaska, because of a reduction in transit time between Asia and Europe. The Northwest

Passage is 7,000 nm shorter than using the Panama Canal and 12,000 nm shorter for commercial supertankers that currently have to travel around Cape Horn. This increase in economic activity leads to possible international disputes concerning maritime territorial rights.

Therefore, the U.S. Navy must be prepared to operate in the Arctic when ice-free conditions exist. This means continuing research in order to correctly model and understand the oceanographic and meteorological dynamics of the region. There is also a critical need to modify/improve current weapon systems, ships, and communication systems in the Navy, or create new ones to operate effectively under such harsh environmental conditions. The U.S. Navy's current capability, acting under ice free conditions, would not be able to maintain its high level of dominance without proper preparations. Therefore, this thesis research aims to support the Navy's research effort in preventing it from being ill equipped and unprepared to operate in an ice free Arctic. This thesis analyzed new model data on increased fresh water output from the Arctic Ocean, exported through the Canadian Arctic Archipelago and the pathway stretching from the Fram Strait into the Labrador Sea. The increased amount of fresh water leaving the Arctic is a good indicator of sea-ice melt and the onset of ice free conditions, which will allow for a navigable Arctic, Northwest Passage and Northern Sea Route. Therefore, the results of this thesis directly support the Navy's effort in preparation for an ice-free Arctic Ocean.

II. MODEL DESCRIPTION

A. OCEAN MODEL

The model is based on a horizontal, rotated spherical grid covering 1280 x 720 points at a 1/12 degree or ~9.26 km resolution with vertical depth coverage down to 6250 m. The model represents all ice covered regions in the Northern Hemisphere including the Arctic Ocean; all sub arctic seas, the Sea of Japan, the Sea of Okhotsk, and all oceanic pathways into and out of the Arctic Ocean. The depth axis is subdivided into 45 levels with varying depth thickness, from 5 to 300 m, based upon dynamical activity at certain depths (Table 2.1).CHECK ALIGNMENT ALL THE WAY…

This regional ocean model was improved from Semtner and Chervin’s (1992) global ocean model and then updated with the Los Alamos National Laboratory (LANL) Parallel Ocean Program (POP) model (Dukowicz and Smith, 1994). The model incorporates a free surface approach, which allows unsmoothed topography (Killworth et al., 1991; Semtner, 1995, Dukowicz and Smith, 1994). This condition is combined with an assumption of hydrostatic balance using Bousinessq approximation. Finite differencing is determined using the Arakawa B-grid (Mesinger and Arakawa, 1976).

The model was initialized from rest with data sets of temperature and salinity from the University of Washington Polar Science Center Hydrographic Climatology 1.0 (PHC) (Steele et al., 2000). During the first 27 Years of the spin up integration the model was forced by climatological data derived from the 1979-1993 European Centre for Medium-Range Weather Forecasts (ECMWF) reanalysis, at a time step of 8 minutes for all levels. However, because the rate of

change of salinity and temperature values at depth is slow, the time step for the second decade of spin up for water below 220m was gradually increased to as much as ten times that of the surface layers. This effectively resulted in a 100-year simulation during only 10 years of model integration. However, after the second decade of spin up the rest of simulation the time step for all depth levels were returned to 8 minutes. The following 21-year spin up repeated the realistic 1979-1981 ECMWF data to prepare the model for the final 1979-2002 interannual forcing run. Since the forcing data used covers a time span associated with positive and negative AO/NAO phases the model results can be assumed unbiased towards any particular atmospheric regime.

The model uses closed boundaries and assumes non-slip conditions at the lateral walls. This provides for a closed system where there is no mass flux through the lateral boundaries or through the bottom boundary. However, the model does account for boundary terms due to river runoff from major rivers, which feed into the Arctic Ocean. These rivers include: the Dvina, Pechora, Ob, Yenisey, Kotuy, Lena, Indigirka, Kolyma, Mackenzie and Yukon Rivers. The model also utilizes prescribed dye-type (passive) tracers to follow riverine inputs, Pacific and Atlantic waters throughout the Arctic Basin. The model is considered eddy permitting, as it is able to resolve eddies with diameters as small as ~37 km.

Layer	Thickness	Lower depth	Midpoint
1	5.0	5.0	2.5
2	5.0	10.0	7.5
3	5.0	15.0	12.5
4	5.0	20.0	17.5
5	6.0	26.0	23.0
6	7.3	33.3	29.7
7	8.8	42.1	37.7
8	10.6	52.7	47.4
9	12.8	65.4	59.1
10	15.4	80.8	73.1
11	18.6	99.4	90.1
12	22.4	121.8	110.6
13	27.0	148.9	135.4
14	32.6	181.5	165.2
15	39.3	220.8	201.2
16	47.5	268.3	244.6
17	57.3	325.5	296.9
18	69.1	394.6	360.1
19	83.3	477.9	436.3
20	100.5	578.4	528.2
21	121.6	700.0	639.2
22	150.0	850.0	775.0
23	200.0	1050.0	950.0
24	200.0	1250.0	1150.0
25	200.0	1450.0	1350.0
26	200.0	1650.0	1550.0
27	200.0	1850.0	1750.0
28	200.0	2050.0	1950.0
29	200.0	2250.0	2150.0
30	200.0	2450.0	2350.0
31	200.0	2650.0	2550.0
32	200.0	2850.0	2750.0
33	200.0	3050.0	2950.0
34	200.0	3250.0	3150.0
35	250.0	3500.0	3375.0
36	250.0	3750.0	3625.0
37	250.0	4000.0	3875.0
38	250.0	4250.0	4125.0
39	250.0	4500.0	4375.0
40	250.0	4750.0	4625.0
41	300.0	5050.0	4900.0
42	300.0	5350.0	5200.0
43	300.0	5650.0	5500.0
44	300.0	5950.0	5800.0
45	300.0	6250.0	6100.0

Table 2.1 Model depth levels and associated thicknesses (m).

B. ANALYSIS METHODS

The analyzed model results are from fourteen different transects in the Canadian Arctic Archipelago (CAA) from 1979 to 2002. The sections are: McClure Strait, Byam Martin Strait, Penny Strait, Dease Strait, Lancaster Sound, Jones Sound, Robeson Strait, Smith Sound, Davis Strait, Foxe/Hecla Strait, Hudson Strait, Hudson Bay Mouth, Pre-Labrador, and Labrador Sea sections (Figure 2.1).

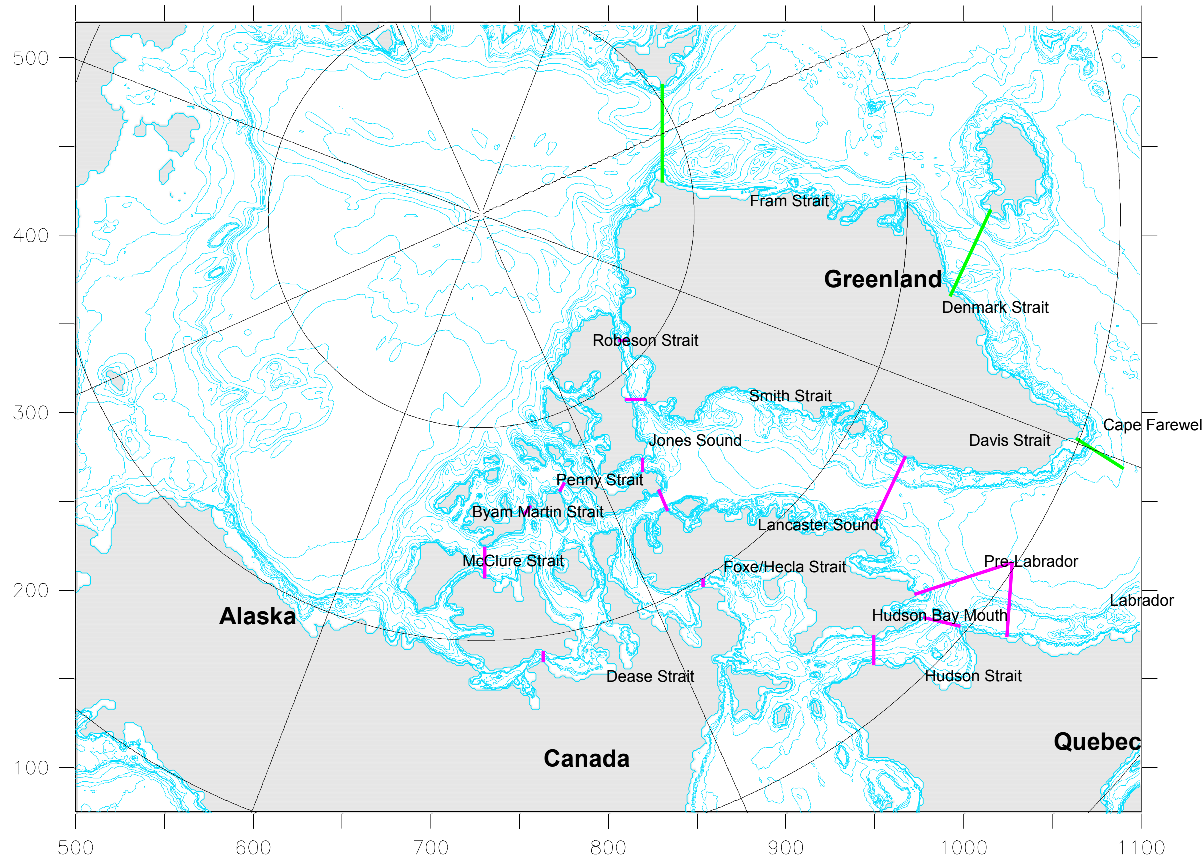

Figure 2.1 Map of sections analyzed.

These pathways collectively account for the total flow through the Canadian Arctic Archipelago. The ability to capture all the water flowing through the CAA from the Western Arctic Ocean into the Labrador Sea is crucial for quantifying volume and freshwater fluxes, entering the Labrador Sea. An additional three sections were analyzed

outside of the Canadian Arctic Archipelago; they were the Fram Strait, the Denmark Strait, and a section off of Cape Farewell. These three sections were used to analyze the freshwater export from the Arctic through its major pathway. However, only the westward flux of water off of Cape Farewell was analyzed because that is the only part which contributes to the Labrador Sea.

Each section had several properties and parameters analyzed. Vertical cross-sections were constructed to determine the depth-dependent flow field, temperature and salinity through the section. The twenty-four-year mean velocity field in cm/s, temperature in $^{\circ}$C and salinity in psu through each section was plotted against depth using a color scheme and contours to show variations in each parameter. A positive velocity was defined, as any flow into the Arctic and a negative velocity was any flow away from the Arctic, or in the case of the Hudson Strait towards the Labrador Sea.

Additionally, time series of monthly mean freshwater, and heat fluxes were calculated across each section for the entire depth over the 24-year time period. The reference salinity used was 34.8 psu and the reference temperature was -0.1 $^{\circ}$C. Freshwater flux values were calculated based upon the reference salinity so that the final result was actual freshwater i.e. 0 psu.

FW_u=vol_u*((s_ref-sal)/s_ref)

Heat fluxes were calculated as:

heat_u=vol_u*(temp-t_ref)

A running mean was also computed for each measured parameter based upon smoothing over a 13-month period along with a 24-year average single value for freshwater and volume flux for each section. In the case of freshwater,

northward and southward fluxes were added for each month then summed over all years and divided by 288 (i.e. 24 years times 12 months per year), to determine the average freshwater flux. A negative freshwater flux is flow out of the Arctic (negative) with a salinity value less than 34.8 psu (positive). A positive flux is caused by freshwater (salinity less than 34.8 psu) flow into the Arctic.

A freshwater annual cycle plot of flux was made for all of the sections by taking an average of the net freshwater value for each month over the 24-year period. In addition, the mean freshwater value averaged for the model data from 1979 to 2002 is included.

Finally, for those sections with a significant volume transport of sea ice, the monthly net ice volume flux along with a 13-month running mean was calculated. The number on the left side of the ice volume flux plots, for example Figure 3.24) is the annual ice volume flux (Sv) calculated over the 24-year time series. The southerly and total ice volume fluxes were computed, with the difference attributed to recirculation. Ice volume flux was converted to liquid freshwater flux taking the model salinity of the sea ice S_{ice} =4 psu and the reference salinity of seawater as S_{water} =34.8 psu (e.g. FW flux = (Ice volume flux*(S_{water} – S_{ice})/ S_{water}) (Östlund and Hunt, 1984). This data was then made into a time series plot and a running mean was overlaid on the plot. The number on the right side corresponds to the 24-year average freshwater flux from sea ice export.

III. RESULTS

A. CANADIAN ARCTIC ARCHIPELAGO

1. Circulation

The general flow of the CAA has not been sufficiently verified by observations due to its harsh environment (Melling et al., 1984). However, from the limited data collected the circulation pattern of the CAA is assumed to begin with cold, fresh, surface waters entering over shallow sills from the Canadian Basin into the CAA (Melling et.al, 1984). The flow moves south on the southwestern sides of the passages into the Northern Baffin Bay, where the relatively fresh, cold water remains trapped on the western side. Once this flow reaches the Labrador Sea it is forms the Labrador Current and continues south above the shelf-break (Cuny et al. 2002). However, using model data the circulation pattern can be better understood and visualized. Analysis of the velocity field, the temperature profile and the salinity profile of each section with depth indicates a common flow pattern throughout the CAA (Figure 3.1).

The sections that are discussed in this section are: Robeson Strait, Smith Strait, Jones Sound, Lancaster Sound, Penny Strait, Byam Martin Strait, McClure Strait, Dease Strait, and the Davis Strait (Figure 2.1). All of these transects show a distinct flow traveling out of the Arctic towards the Baffin Bay. This water is almost all fresher than the reference salinity of 34.8 psu, but there are some variations in salinity values with depth and between different sections.

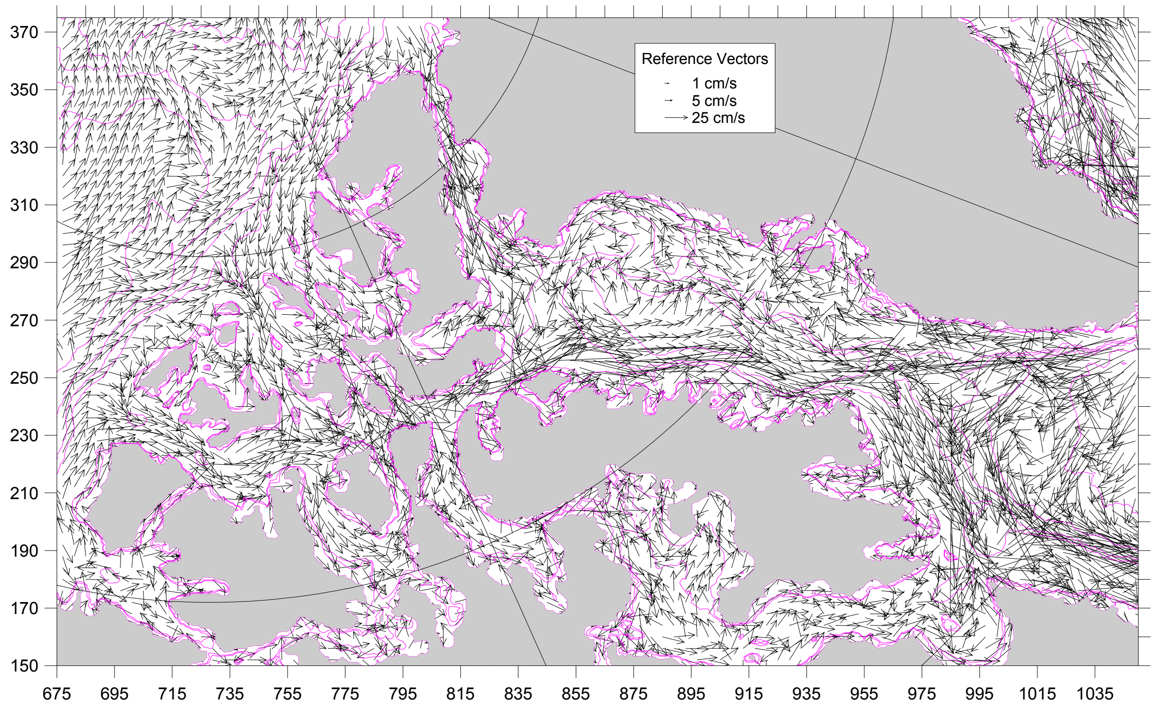

Figure 3.1 24-year averaged circulation over 100m depth with topographic features shown in pink of the CAA.

The CAA has two main outflows into the Northern Baffin Bay, the western side (the so-called Northwest Passage) and the eastern side (the Nares Strait Passage). The western side is mostly water from the McClure Strait flowing into the Lancaster Sound, whereas the eastern side's water flows through Robeson Strait into the Smith Sound. These two outflows have slightly different circulation patterns; however both provide cold, fresh water to the Northern Baffin Bay, which eventually passes south through the Davis Strait.

The McClure Strait is the northern most section of the western CAA analyzed in this study. Its surface layer (about the top 100m), as shown in Figure 3.2 is dominated by a cold, fresh layer moving northwest or into the Arctic. A possible reason for this could be due to local wind

forcing. However, the majority of the freshwater is moving out of the Arctic at deeper depths. The water from the McClure Strait continues towards the Lancaster Sound with inputs from the Byam Martin and Penny Straits. But, by the time the water has reached the Lancaster Sound the circulation pattern has changed in response to local influences.

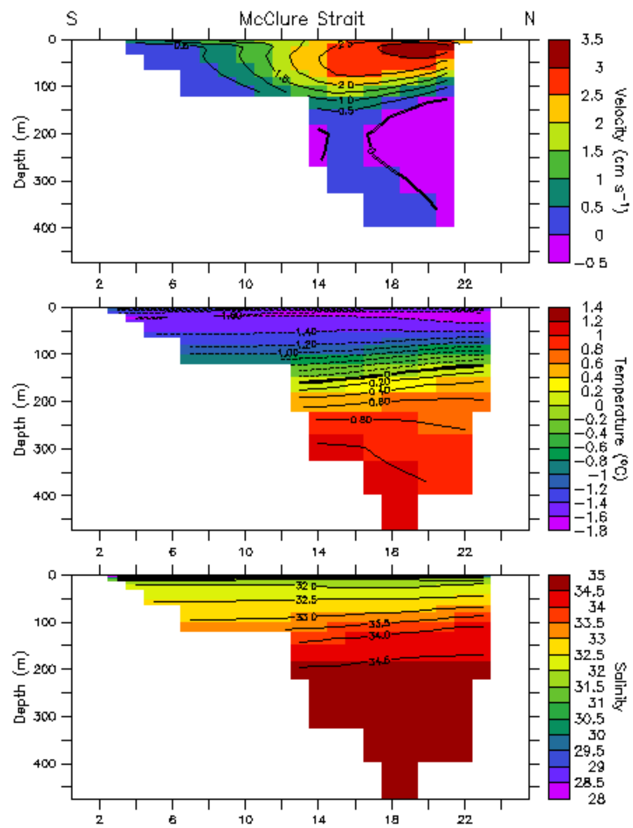

Figure 3.2 24-year average annual velocity, temperature, and salinity profiles for the McClure Strait with negative velocity representing flow away from the Arctic Ocean.

The Lancaster Sound has a structured flow pattern, which shows a distinct flow separation in the middle of the cross-section (Figure 3.3). On the southern part of the section the flow is out of the Lancaster Sound towards the Baffin Bay whilst on the northern side the flow is to the

north. The southern side has very high surface velocities of up to ~22cm/s whereas the northern side has a slower flow with maximum speeds of 8cm/s. The southern side of the Lancaster Sound is slightly less dense than the northern side, which is attributed to colder, fresher water flowing towards the Baffin Bay. The northern side has a slightly warmer and more saline flow due to Atlantic Water brought north by the West Greenland Current.

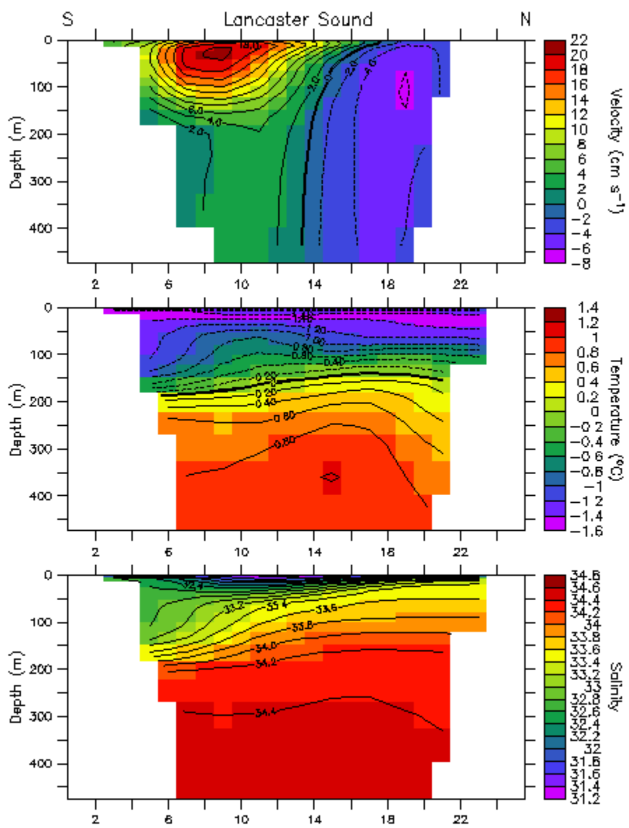

Figure 3.3 24-year average annual velocity, temperature, and salinity profiles for Lancaster Sound with negative velocity representing flow into the Arctic Ocean.

The water entering the CAA from the eastern side of the Arctic Ocean flows through the Robeson Strait before passing through the Smith Sound and then into the Northern Baffin Bay. As seen in the Lancaster Sound the circulation regimes in the Robeson (Figure 3.4) and the Smith (Figure 3.5) also have a separation of current flow. On the eastern side of the two straits there is a northward flow of slow moving, cold, fresh water, whereas on the western side there is a southward moving current. It is possible that the northward movement of water could be due to local wind forcing.

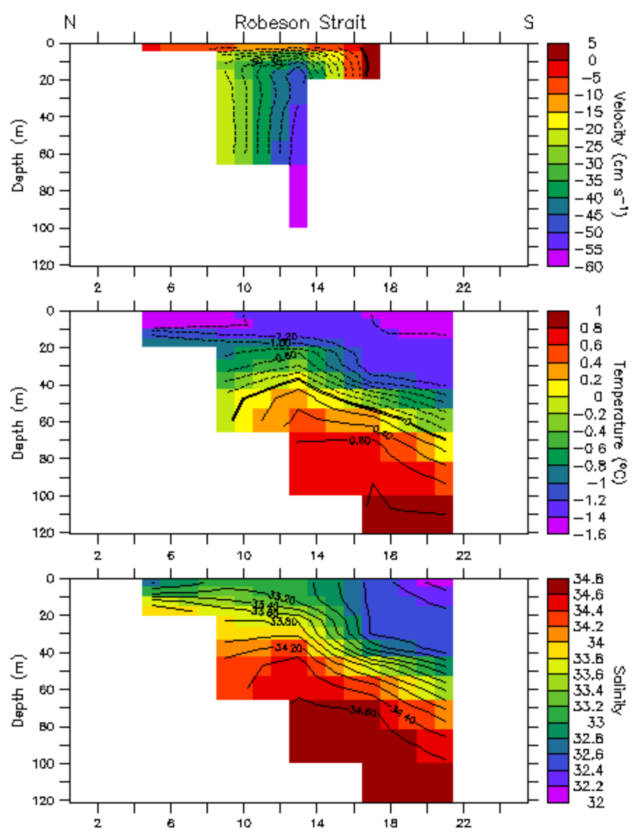

Figure 3.4 24-year average annual velocity, temperature, and salinity profiles for Robeson Strait with negative velocity representing flow away from the Arctic Ocean.

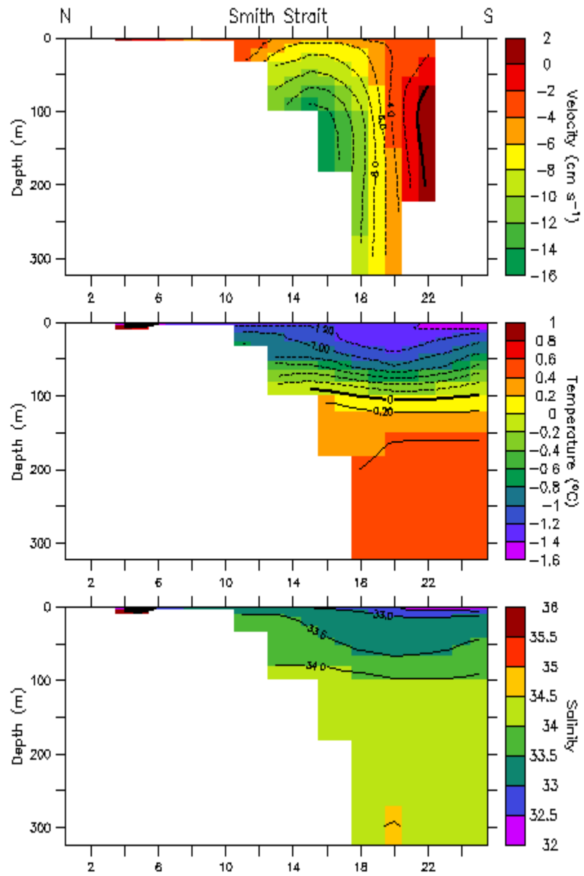

Figure 3.5 24-year average annual velocity, temperature, and salinity profiles for Smith Sound with negative velocity representing flow away from the Arctic Ocean.

The Davis Strait like the circulation regimes of the two major pathways into the Northern Baffin Bay, i.e. the Lancaster and Smith Sounds has a similar distinctive flow pattern (Figure 3.6). The eastern side has warmer, saline water moving northward over the Greenland continental shelf. Then off the shelf, where the depth increases, the flow regime switches indicating a southerly movement of a

much fresher and colder water mass from the Arctic

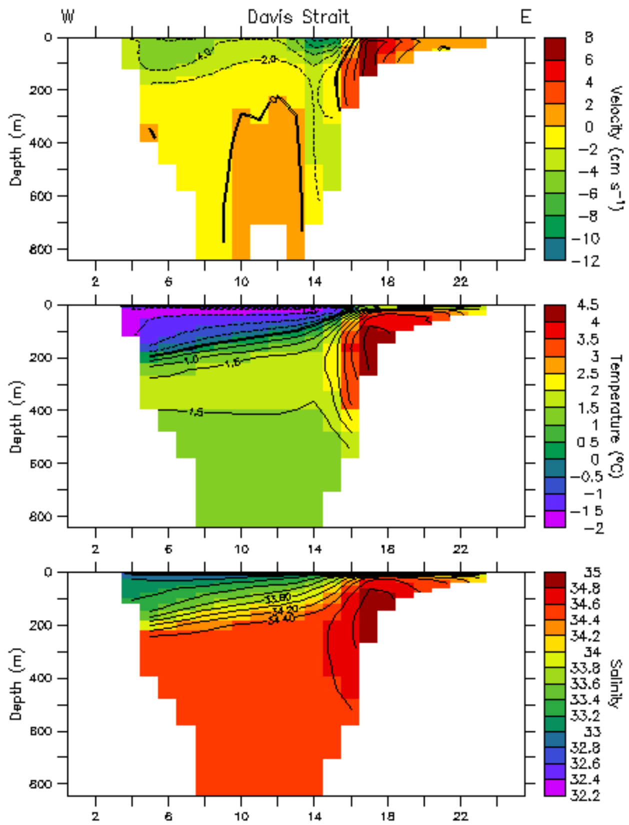

Figure 3.6 24-year average annual velocity, temperature, and salinity profiles for Davis Strait with negative velocity representing flow away from the Arctic Ocean.

Ocean. This southerly moving fresh water is a combination of water from the western and eastern parts of the CAA. Once this water passes through the Davis Strait it continues moving southwards along the western side of the Labrador Sea and forms the Western Labrador Current.

2. Volume, Freshwater, and Heat Fluxes

Analysis of the 24-year time series of volume flux through each section shows that absolute (with respect to

the entire record) maxima and minima occurred at the same time almost throughout the entire CAA (Table 3.1). The majority of the sections had a minimum volume flux between 1980 and 1981 and a relative minimum flux in 1999.

Location	Maximum	Minimum	Relative Minimum
Robeson Strait	1990-1991	1981	1999
Smith Strait	1990-1991	1981	1999
Penny Strait	1990-1991	1980-1981	1989, 1999
Byam Strait	1990-1991	1980-1981	1986, 1999
McClure Strait	1990-1991	1989	1999
Jones Sound	1990	1999	1982
Lancaster Sound	1990-1991	1982	1999
Davis Strait	1990-1991	1981	1999
Foxe/Hecla	1989	1981	1999
Hudson Strait	1989	1998	1994

Table 3.1 Years of the maximum and minimum volume fluxes for straits in the CAA during 1979-2002.

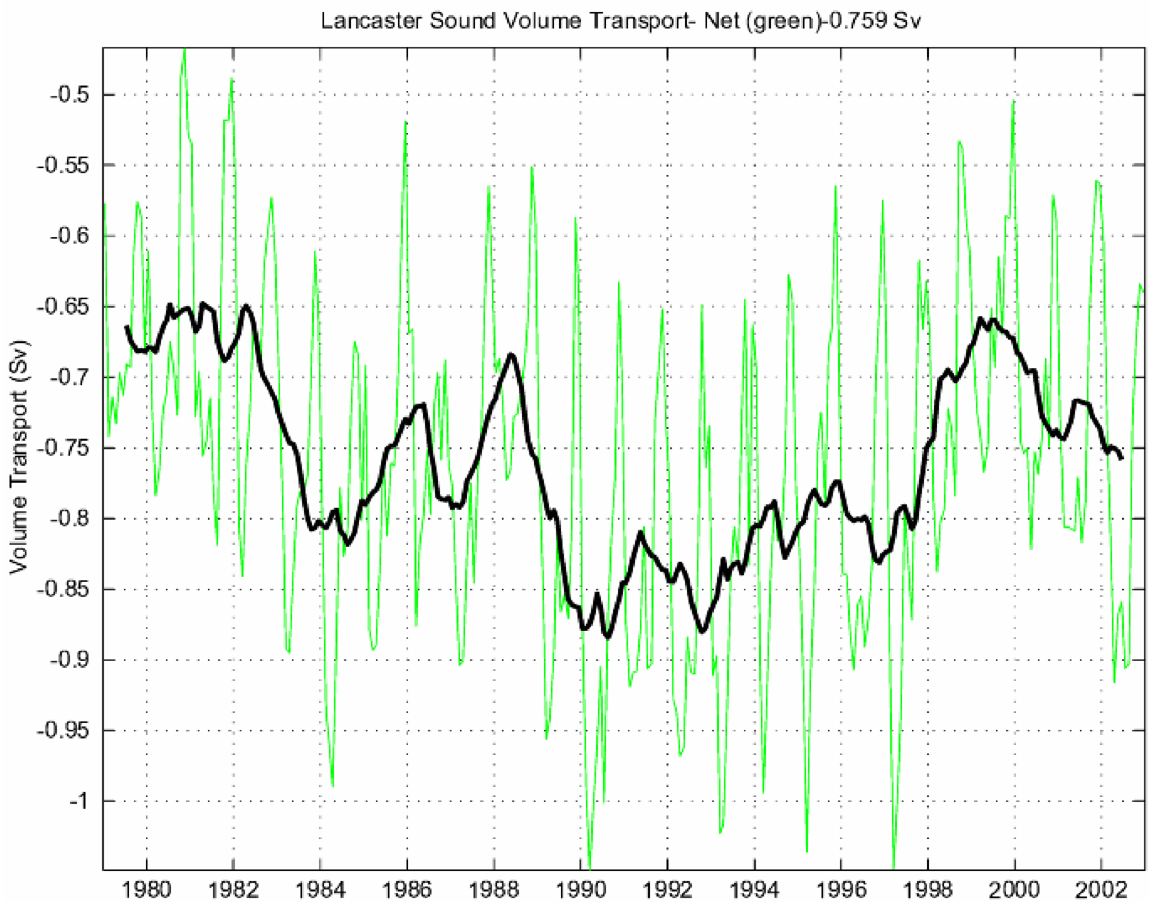

Figure 3.7 1979-2002 monthly mean (green) and 13-month running mean (black) volume flux through the Lancaster Sound. Negative values represent flow away from the Arctic Ocean.

The only exceptions were McClure Strait and Jones Sound (Table 3.1). McClure had its minimum volume flux in 1989 but its relative minimum did coincide with the other sections in 1999. Jones Sound had its minimum volume flux in 1999 and its relative minimum in 1982. The maximum volume flux happened between 1990 to 1991 for all of the stations. An example of this can be seen in Figure 3.8 showing Davis Strait's maximum volume flux occurring between 1990-1991.

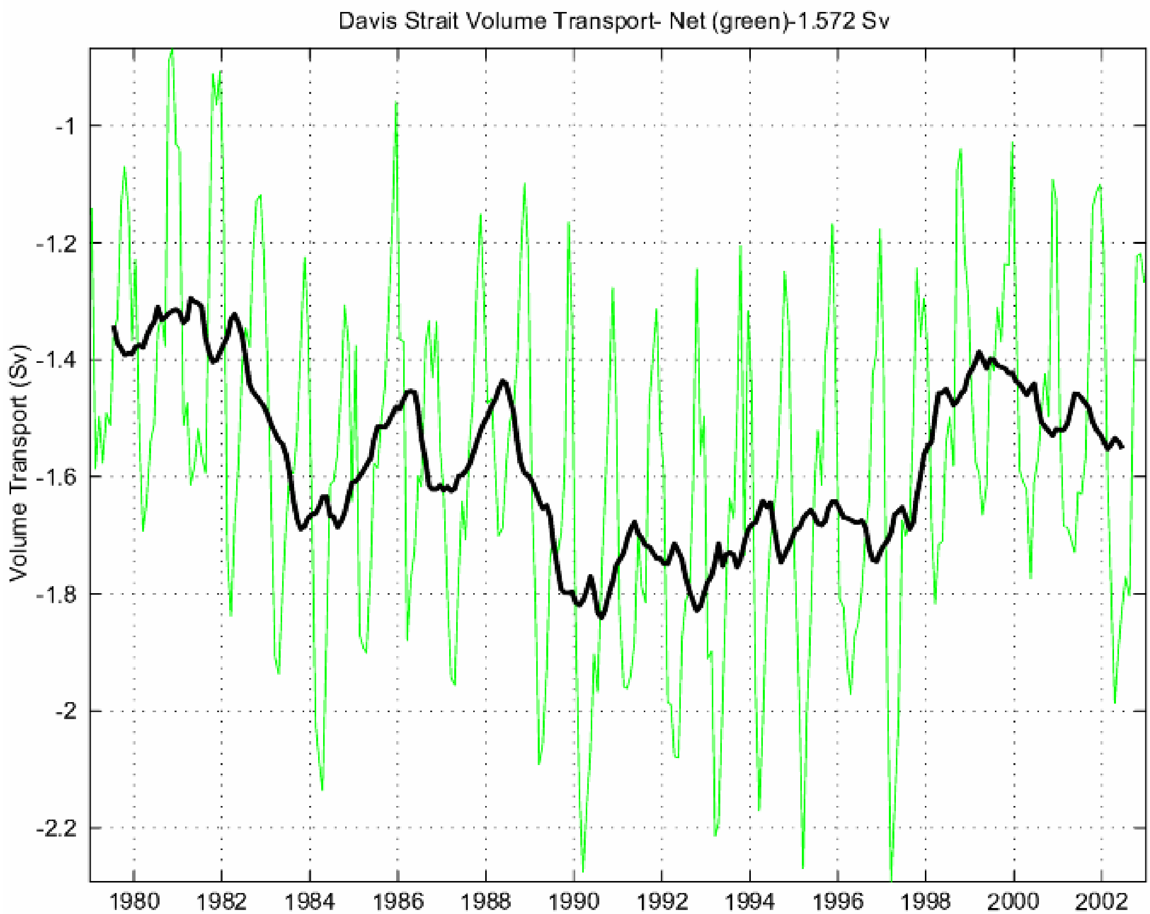

Figure 3.8 1979-2002 monthly mean (green) and 13-month running mean (black) volume flux through the Davis Strait. Negative values represent flow away from the Arctic Ocean.

The maxima and minima volume fluxes had a lot of agreement with the timing of the extreme freshwater fluxes. In the McClure Strait, Jones Sound, Lancaster Sound, and the Davis Strait absolute minimum freshwater fluxes occurred in 1999 shown in Table 3.2.

Location	Maximum	Relative Maximum	Minimum	Relative Minimum
Robeson Strait	1990	1997	1981	1985
Smith Strait	1997	1990	1980-1981	1986
Penny Strait	1990	1984	2000	1980-1981
Byam Strait	1989	1991	1981	1999
McClure Strait	1981	1984, 1990	1999	1988-1989
Jones Sound	1984	1997	1999	1981
Lancaster Sound	1990	1984	1999	1981
Davis Strait	1990	1984,1997	1999	1981
Foxe/Hecla	1989	2001	1981	1994
Hudson Strait	1991	1981	1998	1985

Table 3.2 Years of maximum and minimum freshwater fluxes for sections in the CAA during 1979-2002.

The relative minima occurred in these same sections in 1981. Byam Martin Strait had the absolute minimum freshwater flux in 1981 and a relative minimum in 1999. Penny Strait did not have its minimum until 2000 but the relative minimum occurred in 1981, like the other straits. Interestingly, the Robeson and Smith Straits had a minimum annual flux in 1981. Maximum freshwater fluxes occurred in 1990 for the Davis Strait, Lancaster Sound, Robeson Strait,

Penny Strait, and an example of this is shown in Figure 3.9. McClure Strait and Smith Strait did not have their absolute maximum flux in 1990 but their relative maxima did, see Table 3.2.

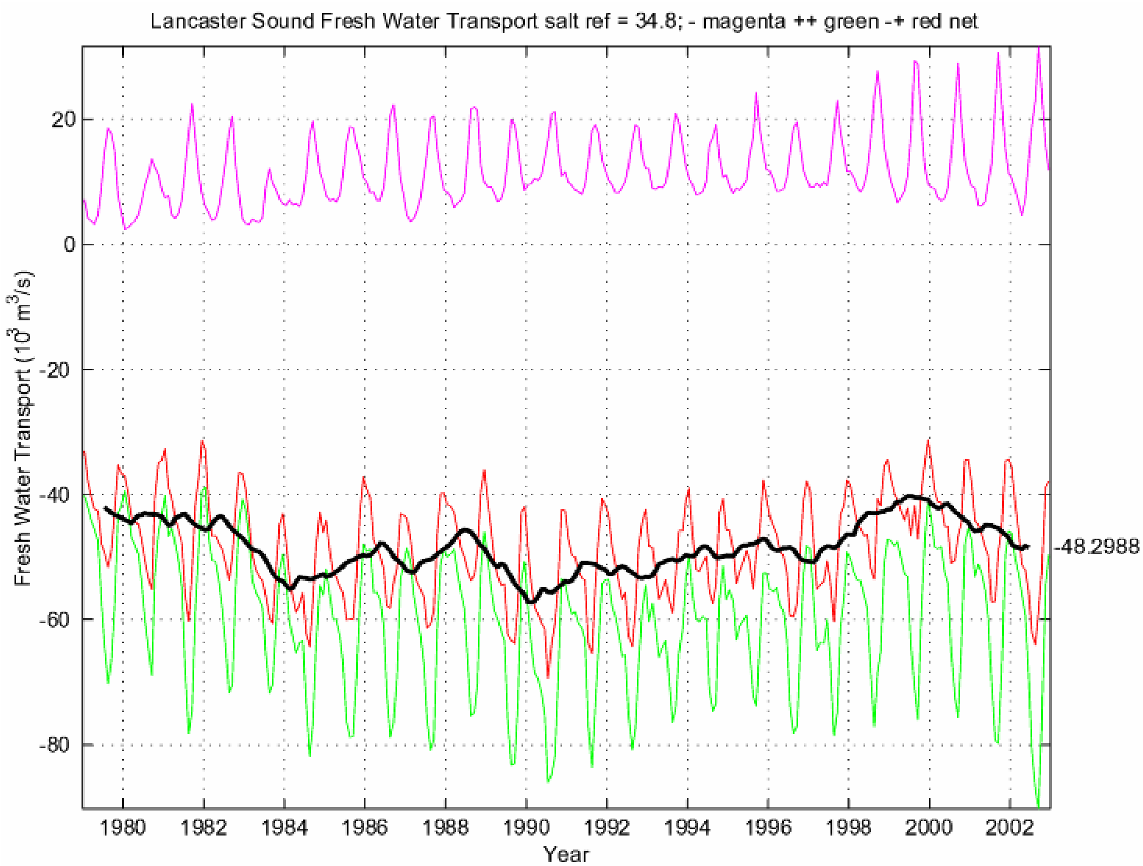

Figure 3.9 24-year average annual freshwater fluxes for the Lancaster Sound. Minimum flux occurs in 1999 and maximum occurs in 1990 with negative values representing flow away from the Arctic Ocean. The magenta line indicates flow of water less saline than 34.8 psu into the Arctic. The green line indicates flow of water less than 34.8 psu out of the Arctic. The red line indicates the net flow of water and the black line shows the 13-month running mean.

An analysis of the heat fluxes over the 24-year period reflects the dominant circulation and current flow through each section. The sign of the heat flux is dependent upon flow direction and the temperature of the water in relation to the reference temperature (-0.1 °C). When describing a

heat flux through a section it is necessary to consider all possible combinations of flow direction, and temperature difference. The maximum heat flux through the McClure Strait, Penny Strait, Jones Sound, and the Lancaster Sound is represented by a flow moving away from the Arctic Ocean and colder than the reference temperature. This agrees with the circulation pattern in this part of the CAA, where most of the flow was found to move out of the Arctic as fresh, cold water. The monthly mean heat flux plot for Lancaster Sound shown in Figure 3.10 is an example of the water which flows through the western CAA. The blue line in Figure 3.10 shows that the dominant flow is colder than the reference temperature water flowing out of the Arctic.

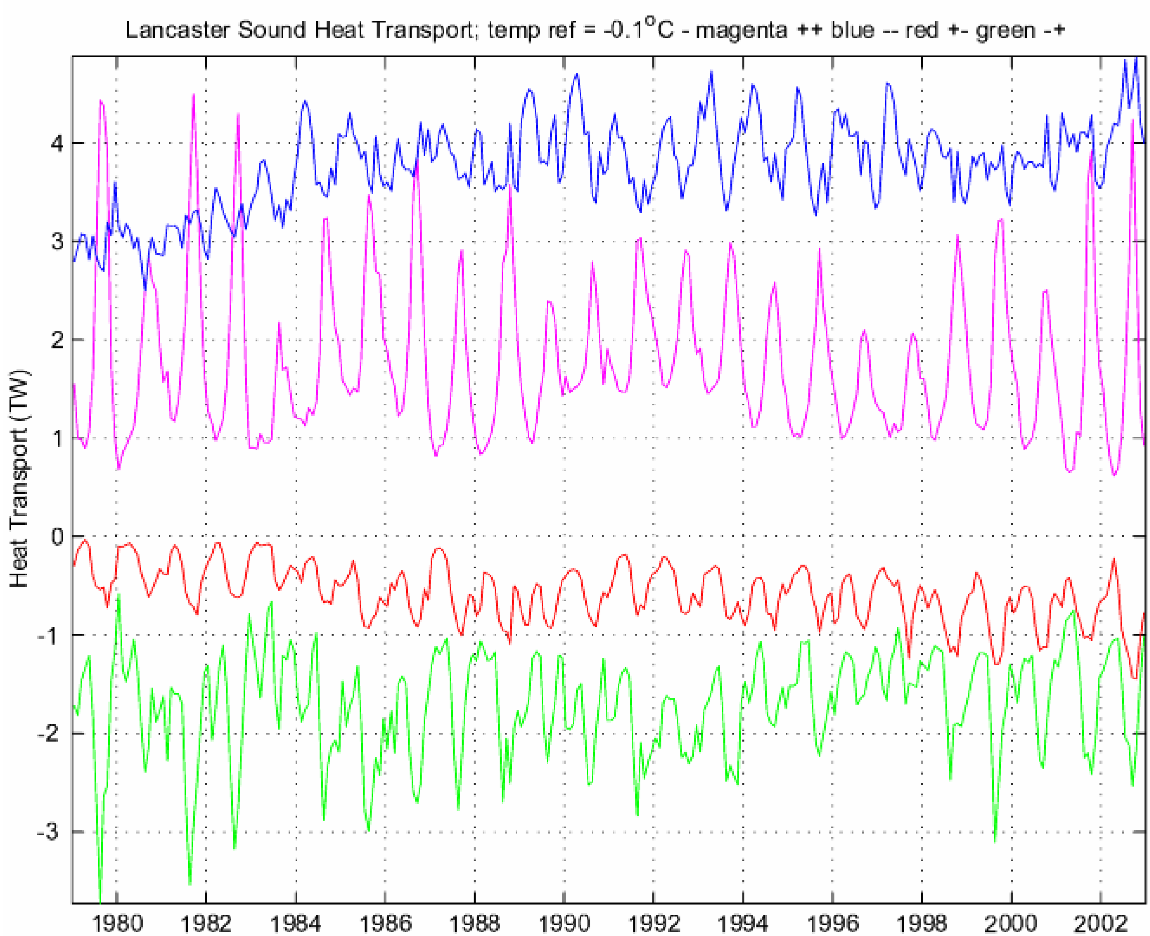

Figure 3.10 1979-2002 monthly mean heat flux for the Lancaster Sound. The magenta line indicates warmer than -0.1 °C water moving into the Arctic. The blue line indicates colder than -0.1 °C water moving out of the Arctic into the Baffin Bay. The red line indicates colder than -0.1 °C water moving into the Arctic and the green line indicates warmer than -0.1 °C water moving out of the Arctic.

However, the heat flux through the Smith and Robeson Straits (Figures 3.11 and 3.12) shows a significant flow moving south that is warmer than -0.1 °C. Figure 3.11 is the monthly mean heat flux plot for the Robeson Strait and provides an example of the dominant heat flux through the eastern CAA. It is indicated by the green line on the plot representing southward moving water which is warmer than reference temperature. The possible reason for warmer

water to be flowing out of the Arctic into the Northern Baffin Bay will be addressed later in the discussion.

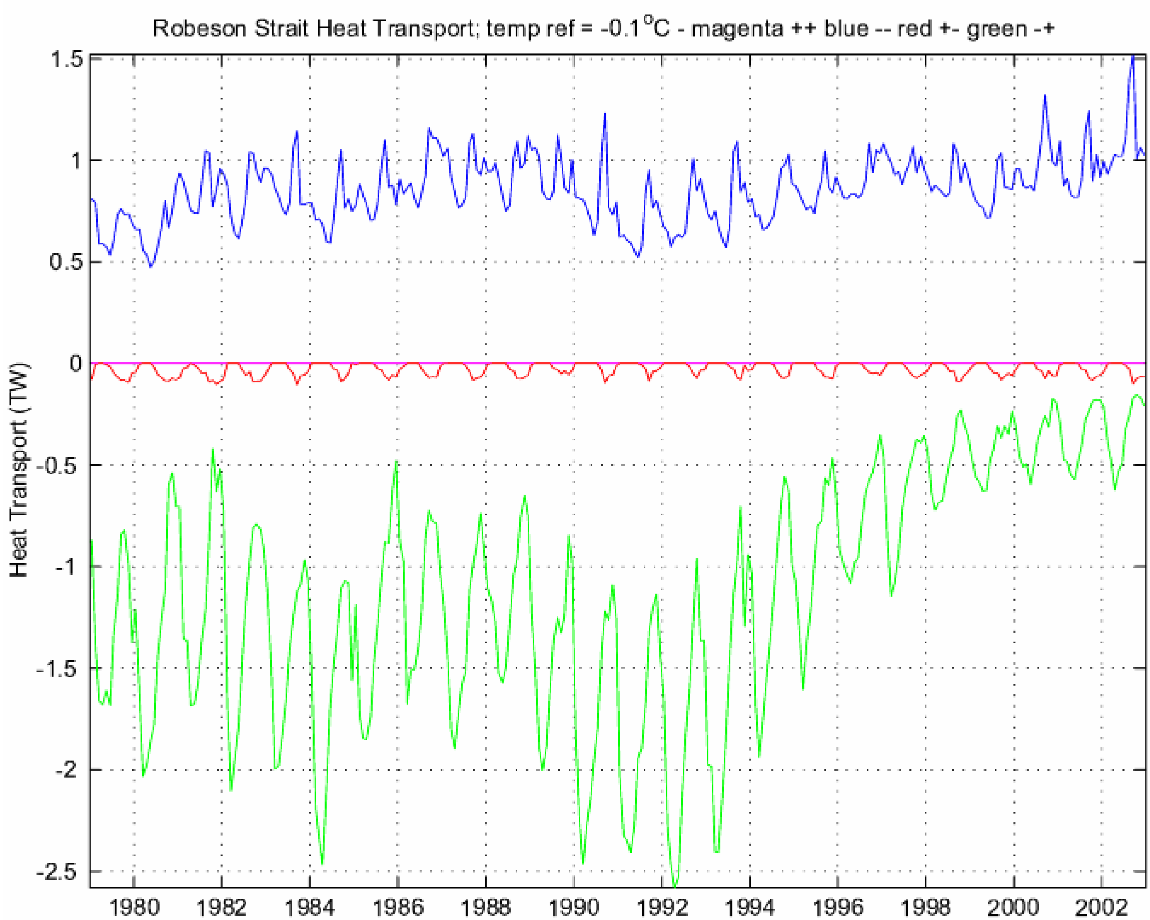

Figure 3.11 1979-2002 monthly mean heat flux for the Robeson Strait. The magenta line indicates warmer than -0.1 °C water moving into the Arctic. The blue line indicates colder than -0.1 °C water moving out of the Arctic into the Baffin Bay. The red line indicates colder than -0.1 °C water moving into the Arctic and the green line indicates warmer than -0.1 °C water moving out of the Arctic.

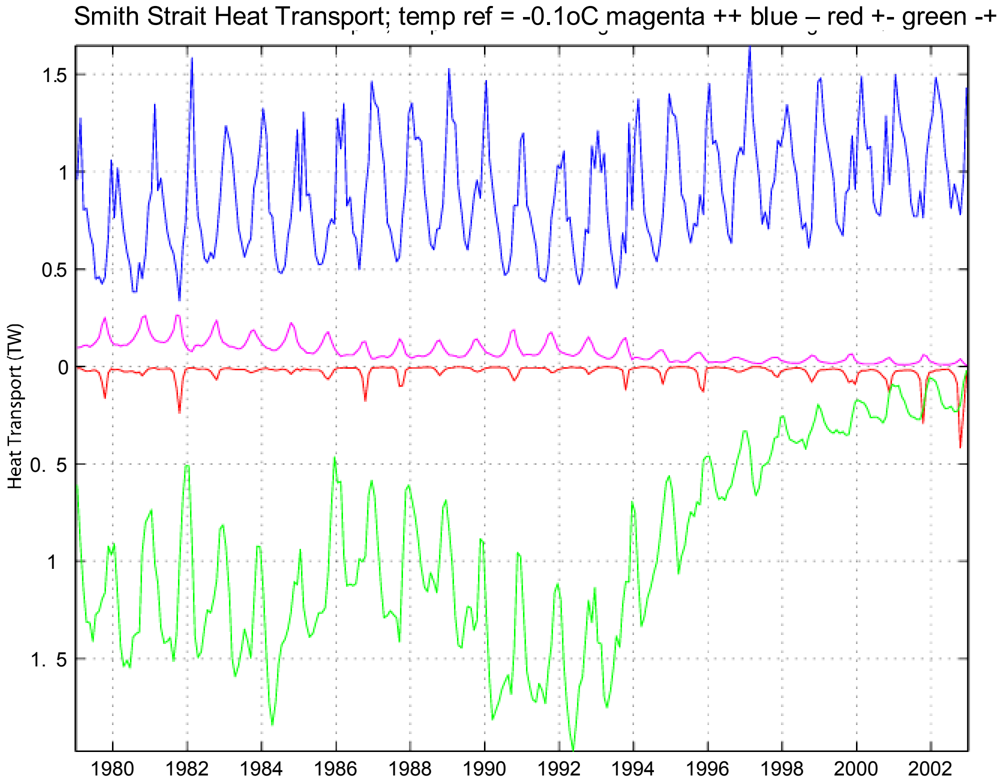

Figure 3.12 1979-2002 monthly mean heat flux for the Smith Strait. The blue line indicates colder than -0.1 °C water moving out of the Arctic into the Baffin Bay. The red line indicates colder than -0.1 °C water moving into the Arctic and the green line indicates warmer than -0.1 °C water moving out of the Arctic.

The heat flux through the Davis Strait is northwards and warmer than the reference temperature (Figure 3.13). This is indicative of the strong influence of the northward, moving warm West Greenland Current has on the total Davis Strait transport.

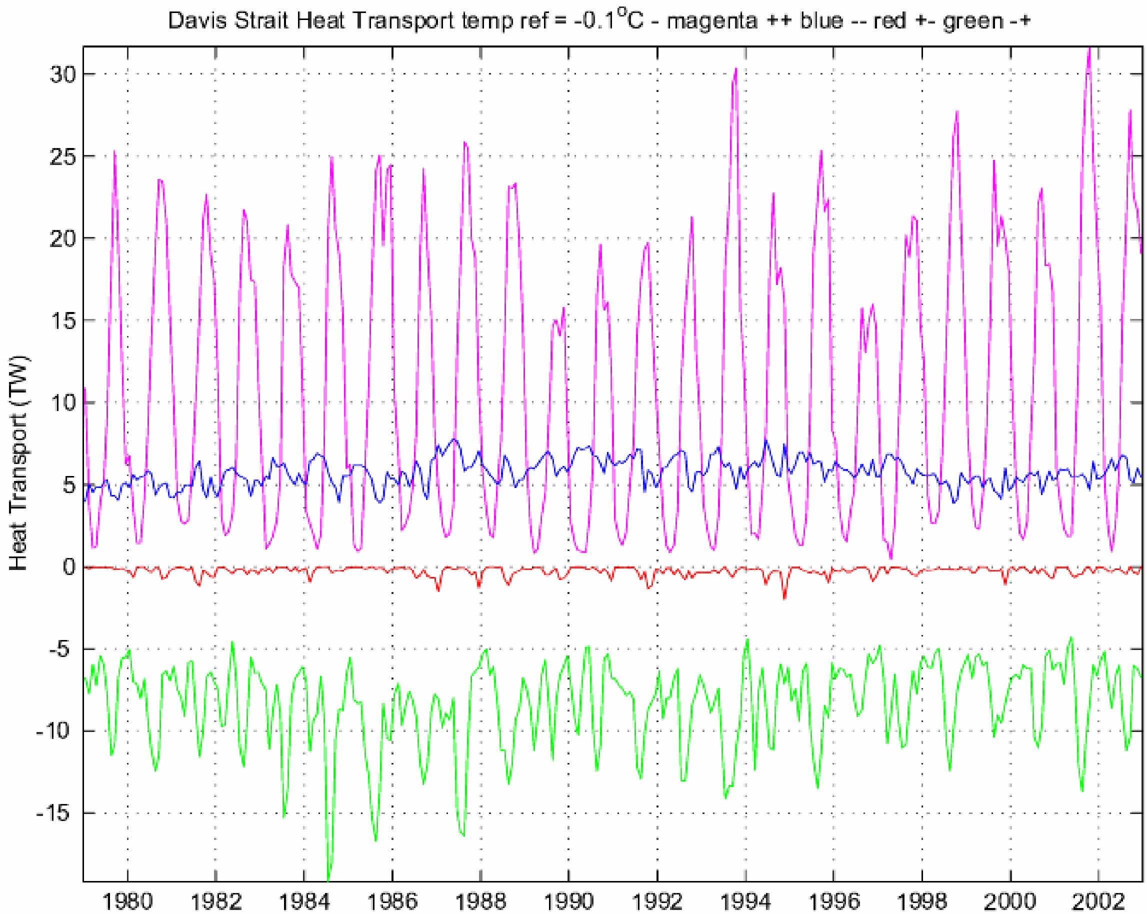

Figure 3.13 1979-2002 monthly mean heat flux for the Davis Strait. The magenta line indicates warmer water moving north into the Arctic Ocean characteristic of the West Greenland Current. The blue line indicates colder than -0.1 °C water moving out of the Arctic into the Baffin Bay. The red line indicates colder than -0.1 °C water moving into the Arctic and the green line indicates warmer than -0.1 °C water moving out of the Arctic.

3. Annual Cycles

The annual cycles for freshwater flux out of the CAA were constructed by computing 24-year averages for each month and for each section. All the sections analyzed show an increase in freshwater flux during the summer months and a decrease during winter. Minima freshwater flux values are associated with local sea ice formation in the winter,

which increases local salinity levels. Likewise, local sea ice melt in each section produces an increase in freshwater fluxes during the summer months. Table 3.3 shows when the maximum and minimum fluxes occurred for each section.

However, in the Robeson, Smith, Penny, and Byam Martin Straits relative maximum fluxes occur during the spring months when the straits are still ice covered. These same straits also have relative minimum fluxes occurring in June, which is a summer month (Figures 3.14, 3.15, 3.16, 3.17). This suggests that local sea ice formation and melt is not the only thing influencing freshwater fluxes in these straits. Further reasoning for this is addressed in the discussion.

Location	Minimum Flux	Relative Minimum	Maximum	Relative Maximum
Robeson Strait	October	June	August	March
Smith Strait	October	June	February	August
Penny Strait	November	June	August	March
Byam Strait	November	June	August	April
McClure Strait	April	N/A	August	September
Dease Strait	December	May	August	N/A
Jones Sound	January	N/A	August	N/A
Lancaster Sound	December	April	August	July
Davis Strait	March	N/A	October	July
Foxe/Hecla Strait	January	June	August	N/A
Hudson Strait	April	N/A	November	August/September

Table 3.3 Months of maximum and minimum freshwater fluxes within the mean annual cycle determined from 1979-2002. N/A is used when there was no significant relative maximum or minimum flux present.

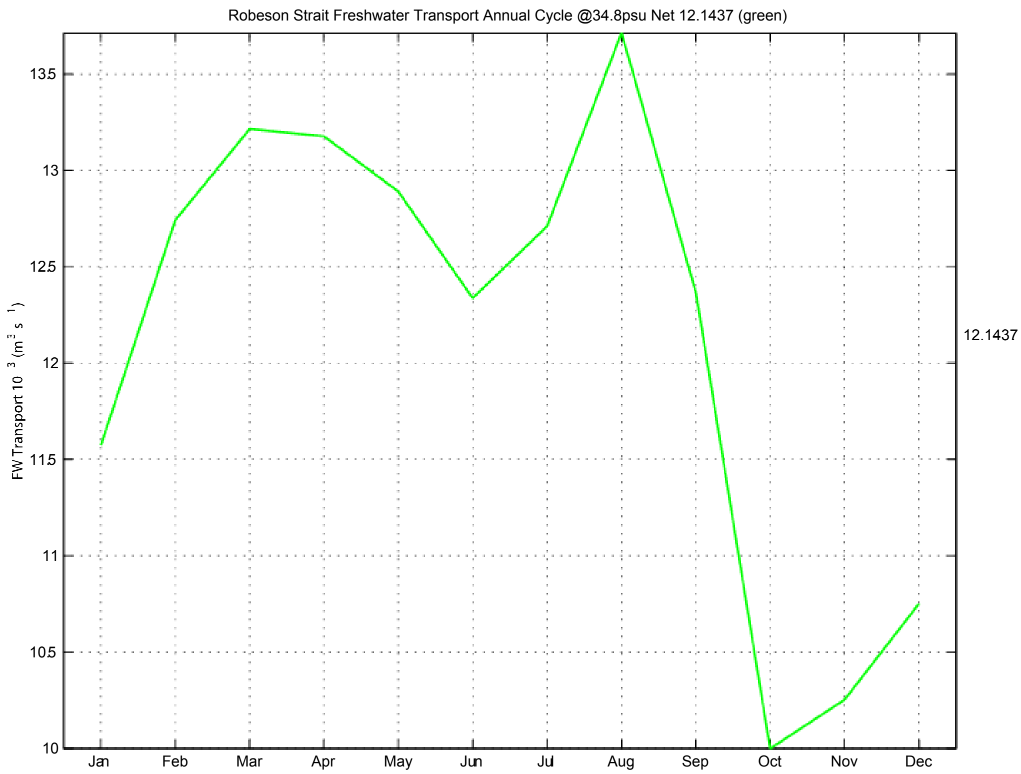

Figure 3.14 24-year mean annual cycle of the freshwater flux (mSv) through the Robeson Strait.

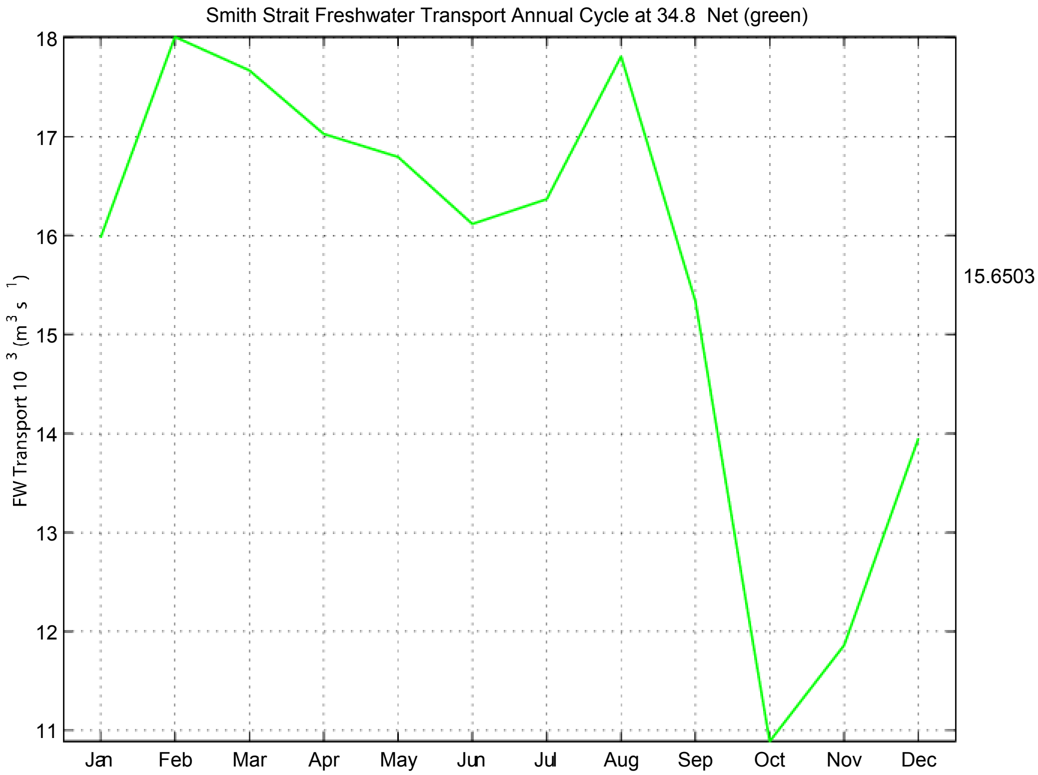

Figure 3.15 24-year mean annual cycle of the freshwater flux (mSv) through the Smith Strait.

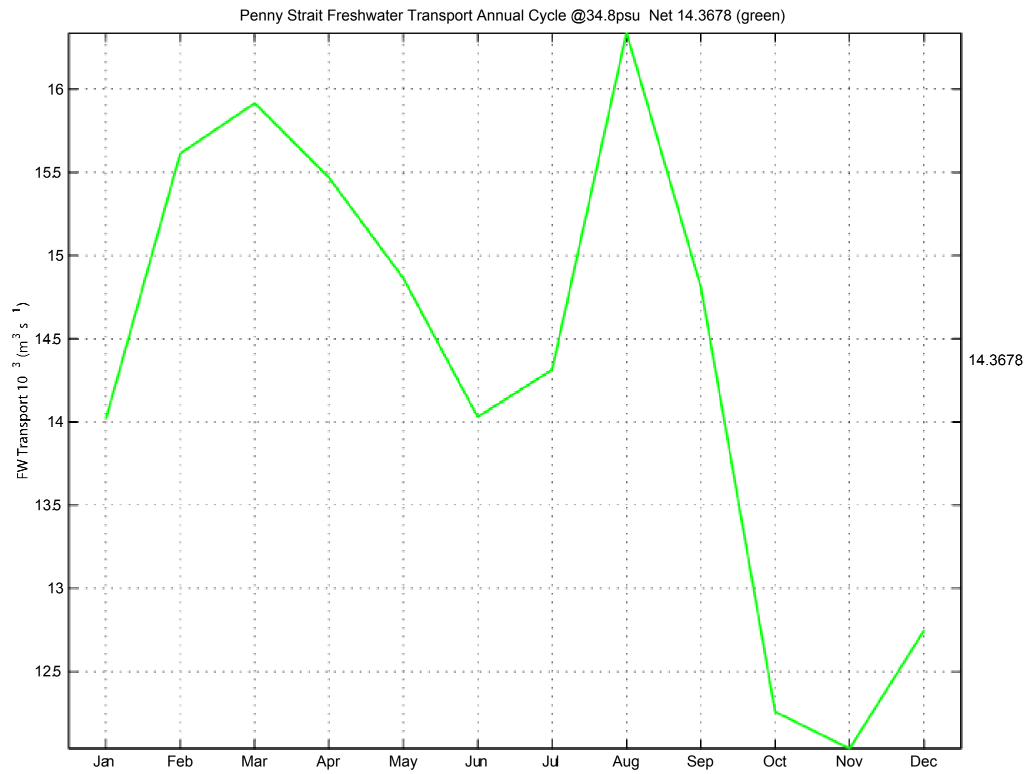

Figure 3.16 24-year mean annual cycle of the freshwater flux (mSv) through the Penny Strait.

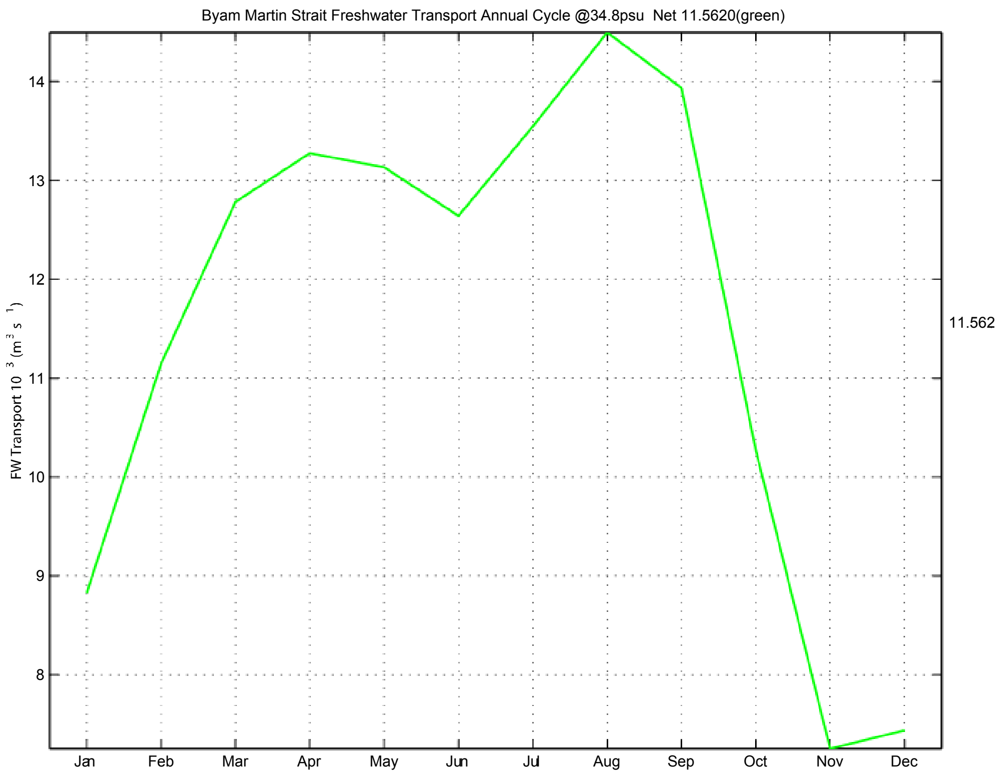

Figure 3.17 24-year mean annual cycle of the freshwater flux (mSv) through the Byam Martin Strait.

B. FRAM STRAIT, DENMARK STRAIT, AND CAPE FAREWELL

Southward and net total volume and freshwater fluxes through the Fram and Denmark Straits were computed separately to show the influence of recirculation on the net annual volume and freshwater fluxes downstream. However, for comparison with other pathways the net volume and freshwater fluxes should be considered as they represent the actual amount of water exiting the Arctic Ocean regardless of the recirculation. Therefore, when evaluating variability of water export through Fram Strait the net volume and freshwater fluxes were used. The southward flux values are informative as they give quantitative amounts of actual water being exported south along the East Greenland Current. Likewise the westward

and net fluxes across the Cape Farewell section were computed separately because of the large amount of mixing occurring in this region with northward moving Atlantic Water. However, the westward flow passing Cape Farewell is of more interest for this study because it quantifies the freshwater contribution from the Arctic Ocean via the Fram and Denmark into the Labrador Sea.

The Fram Strait's 24-year mean net volume flux is 2.337 Sv (Figure 3.18), and the 24-year monthly mean southerly volume flux is 7.08 Sv (Figure 3.19). The net and southerly volume fluxes through the Fram Strait show similar oscillation patterns through the 24-year time series, however the magnitudes of their variations are quite different. The range of variation for the net 13-month running mean volume flux is from about 1.8 Sv to about 2.8 Sv, (Figure 3.18), throughout the time period examined, whereas the southerly flux varied from about 5.6 Sv to 9 Sv (Figure 3.19). The large difference between the net and southerly fluxes and their variations in part is due to the northward flowing West Spitsbergen (WSC) Current and in part due to the recirculation within the Fram Strait. It is worth noting that the recirculation of warm and salty water from WSC has a large effect upon the amount of freshwater flowing south in the East Greenland Current (EGC), through 'salinization' of the surface water masses.

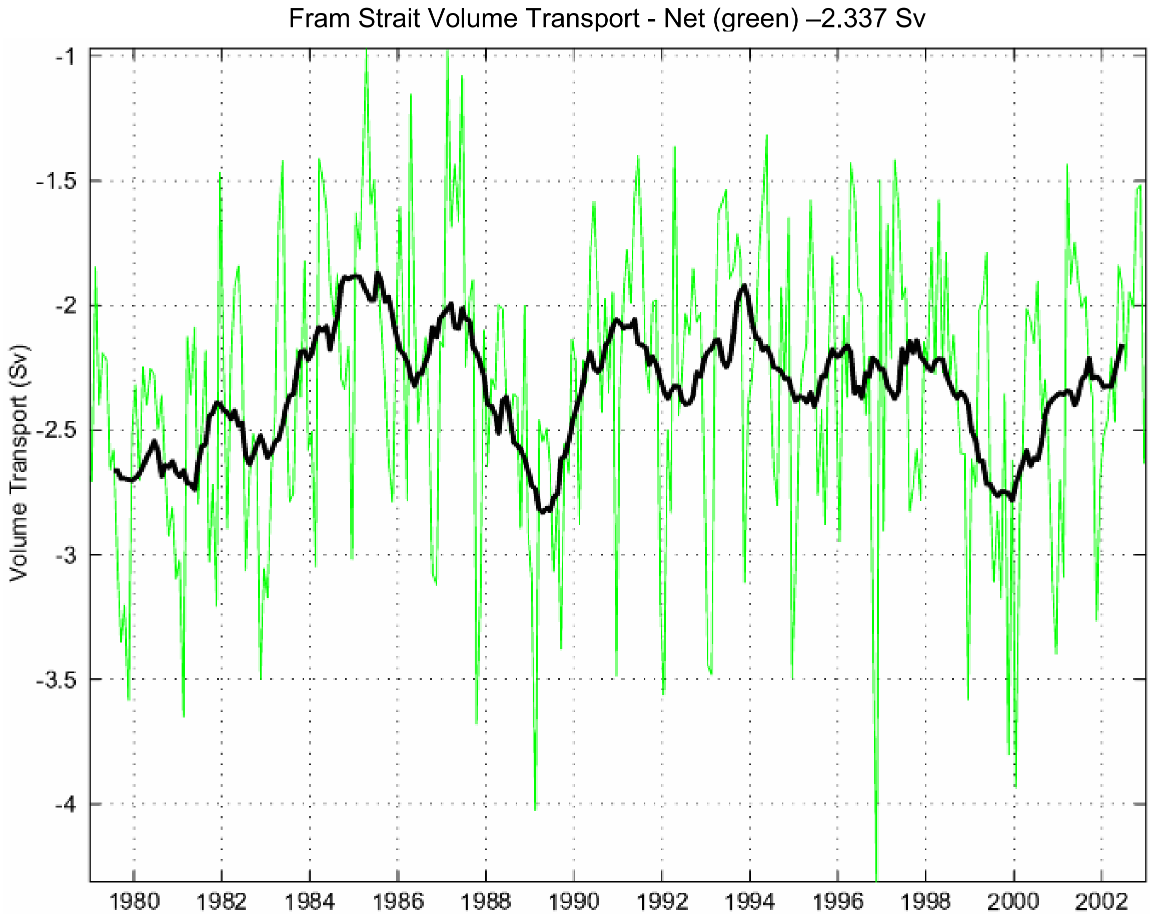

Figure 3.18   1979-2002 net monthly mean (green) and 13-month running mean volume fluxes through the Fram Strait. Negative values indicate southerly flow, or out from the Arctic Ocean.

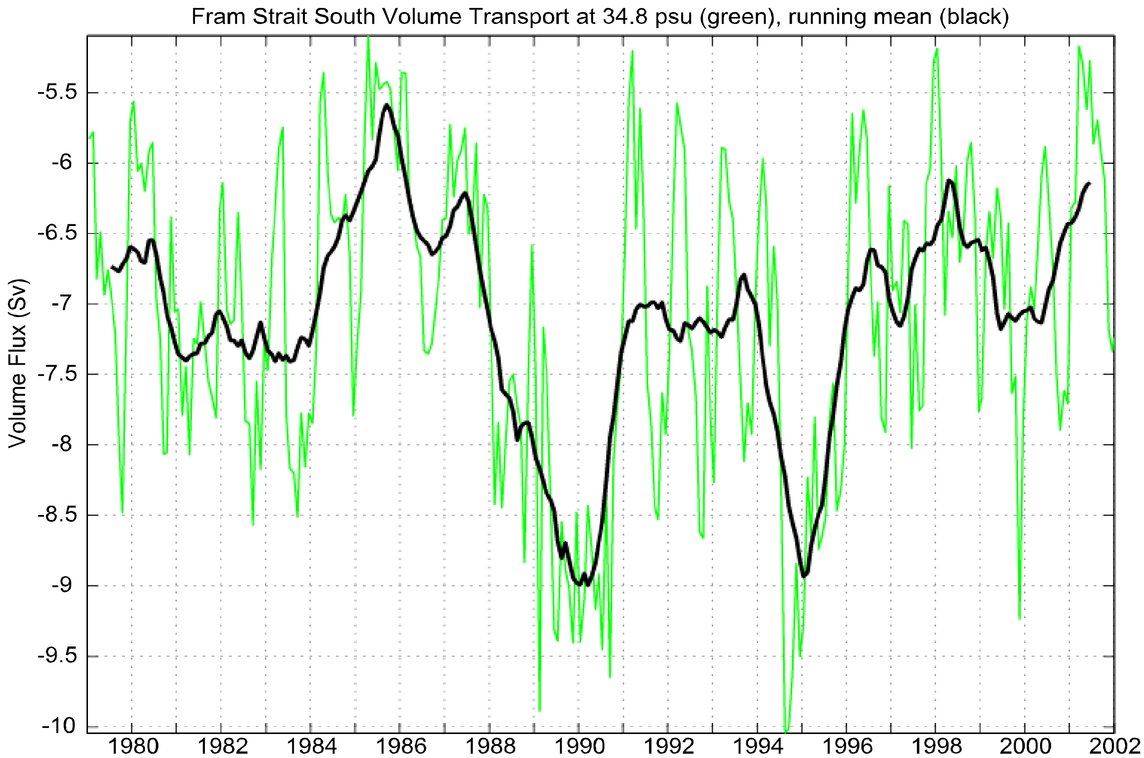

Figure 3.19 1979-2002 southerly monthly mean (green) and 13-month running mean volume fluxes through the Fram Strait. Negative values represent southerly flow.

The lowest freshwater and volume fluxes for the entire time series are modeled in 1985 both for the net and southerly flow across Fram Strait (Figures 3.18, 3.19, 3.20, and 3.21). In 1985 the net freshwater flux the 13-month running mean value drops to ~5m Sv and the net volume to ~1.8 Sv. The net and southerly freshwater fluxes and the net and southerly volume fluxes all experience maximum fluxes in 1989-1990. Yet, in 1994-1995 a minimum flux occurs in the net volume transport but a maximum flux occurs in the net freshwater flux, which shows that the freshwater and volume fluxes are not always in good agreement with each other. Also the southerly volume (7.08 Sv) and freshwater (16.1601 mSv) mean values are greater than their corresponding net mean values of, 2.337 Sv for

net volume and 10.6382 for net freshwater, due to the influence of re-circulation.

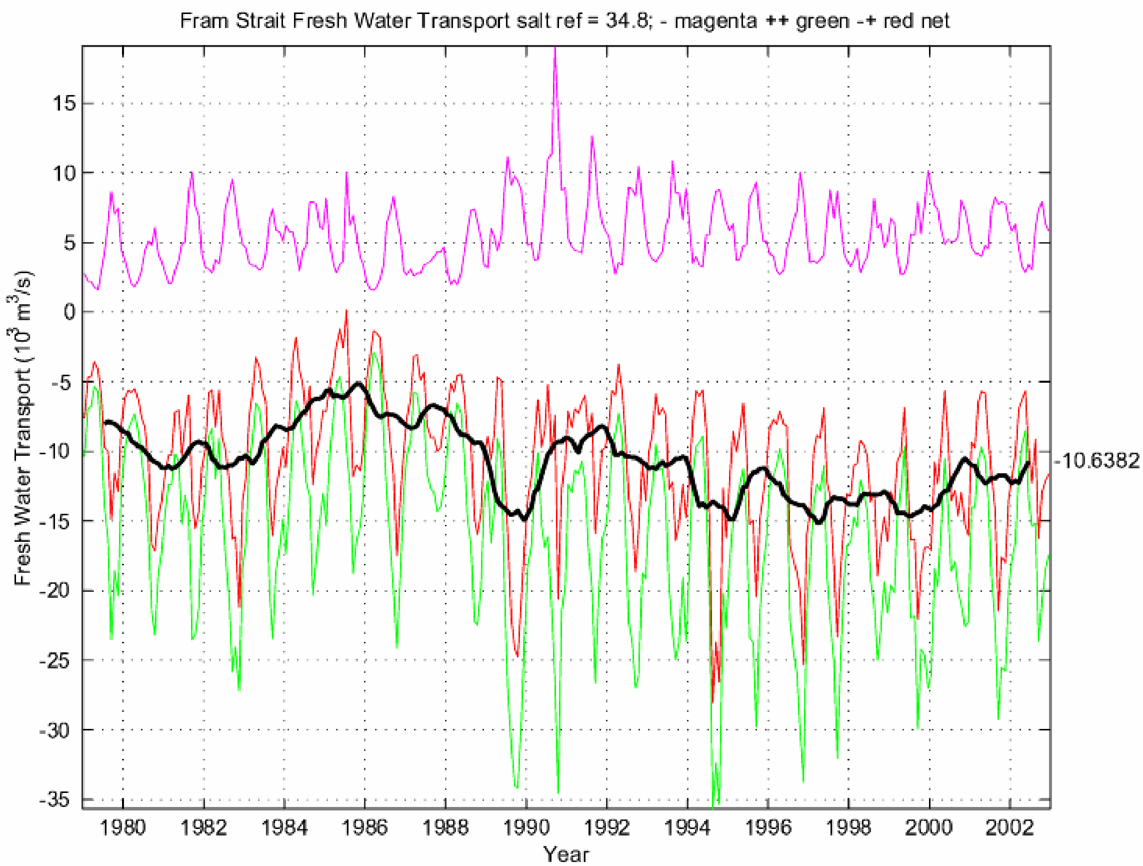

Figure 3.20 1979-2002 monthly mean net freshwater fluxes through the Fram Strait. Negative flux corresponds to southward flow. Water less than 34.8 psu into the Arctic (magenta) water less than 34.8 psu out of the Arctic (green) net flow of water (red) and 13-month running mean (black).

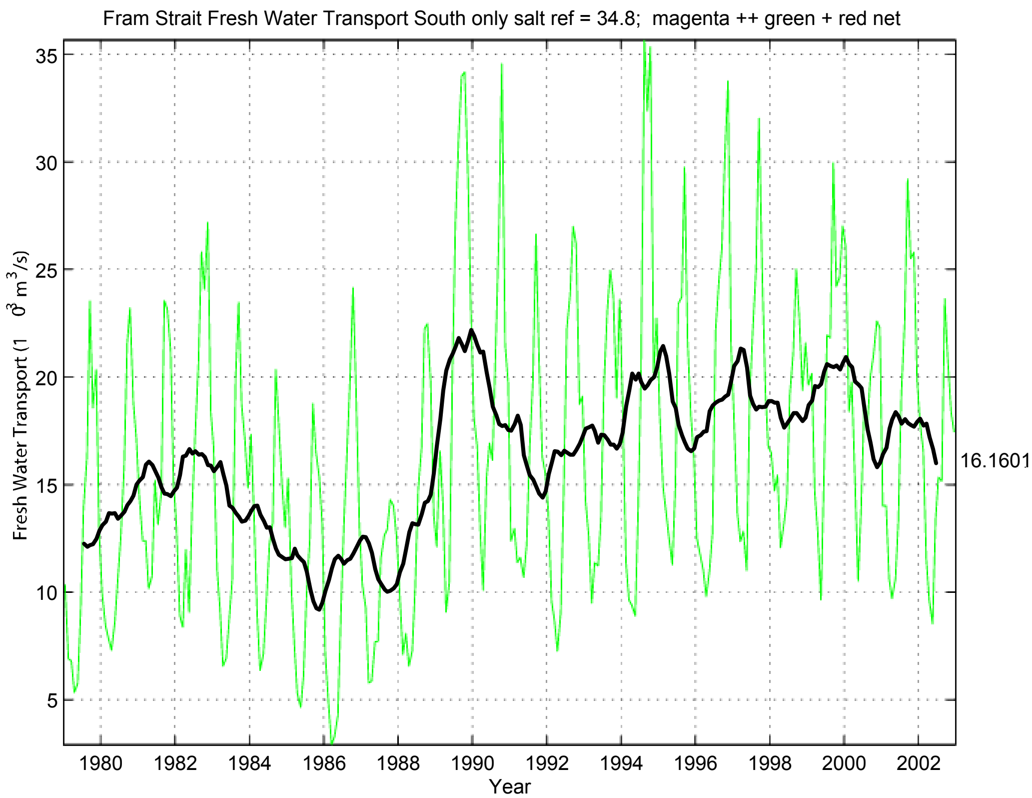

Figure 3.21   1979-2002 monthly mean southerly freshwater flux through the Fram Strait, (green) and 13-month running mean (black).

The minimum flux in 1985 experienced in the Fram Strait shows up downstream in the Denmark Strait (Figure 3.22) and Cape Farewell (Figure 3.23) about two years later in 1987. Both the Denmark Strait and Cape Farewell experience their lowest 13-month running mean freshwater fluxes in 1987 with, ~6mSv, and ~1mSv, respectively. There also appears to be a downstream connection between the maximum values. The Fram Strait experienced its greatest 13-month running mean flux in freshwater around 1997 at ~15mSv. This signal appeared further downstream in the Denmark Strait as a maximum value of about 18mSv in 1999. The second largest freshwater flux for the Cape Farewell

pathway also occurred in 1999 with a 13-month running mean flux of ~4.3mSv.

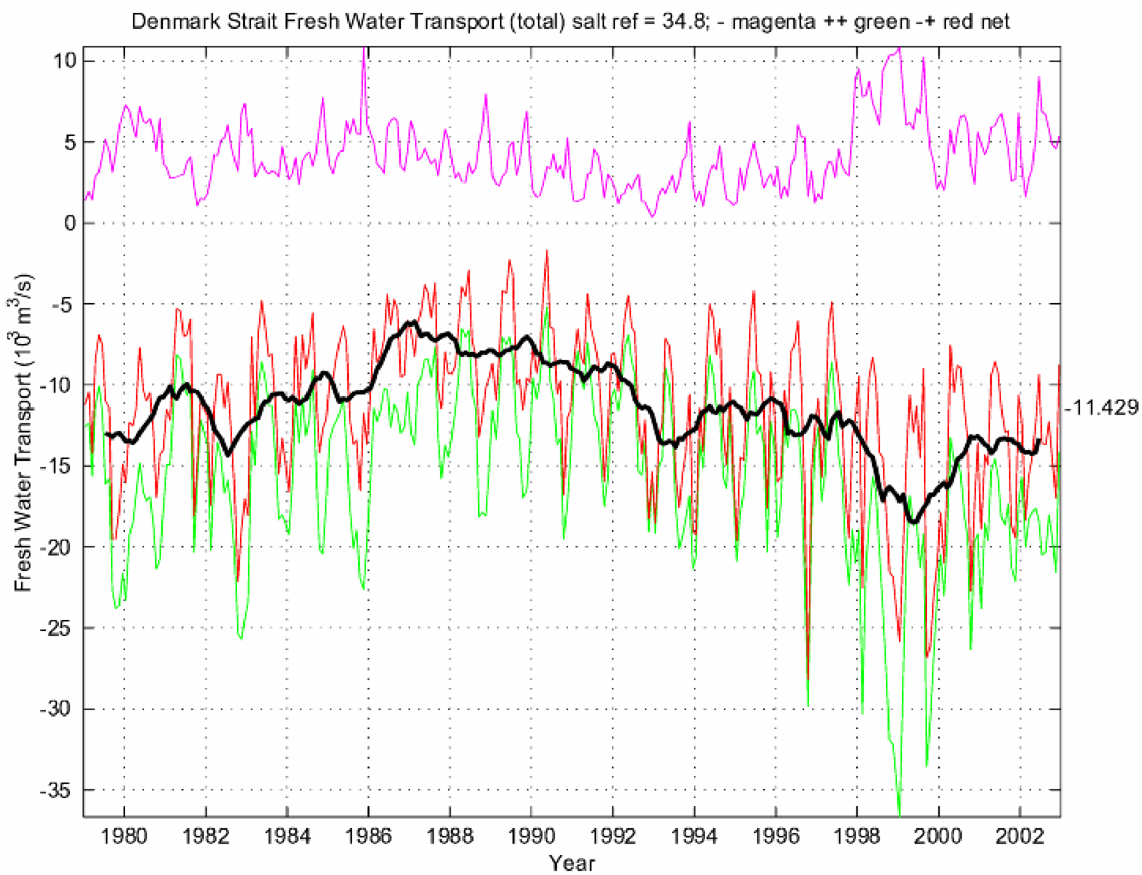

Figure 3.22 1979-2002 monthly mean total freshwater flux through the Denmark Strait minimum flux occurred in 1987 and maximum in 1999. Negative flux corresponds to southward flow. Water less than 34.8 psu into the Arctic (magenta) water less than 34.8 psu out of the Arctic (green) net flow of water (red) and 13-month running mean (black).

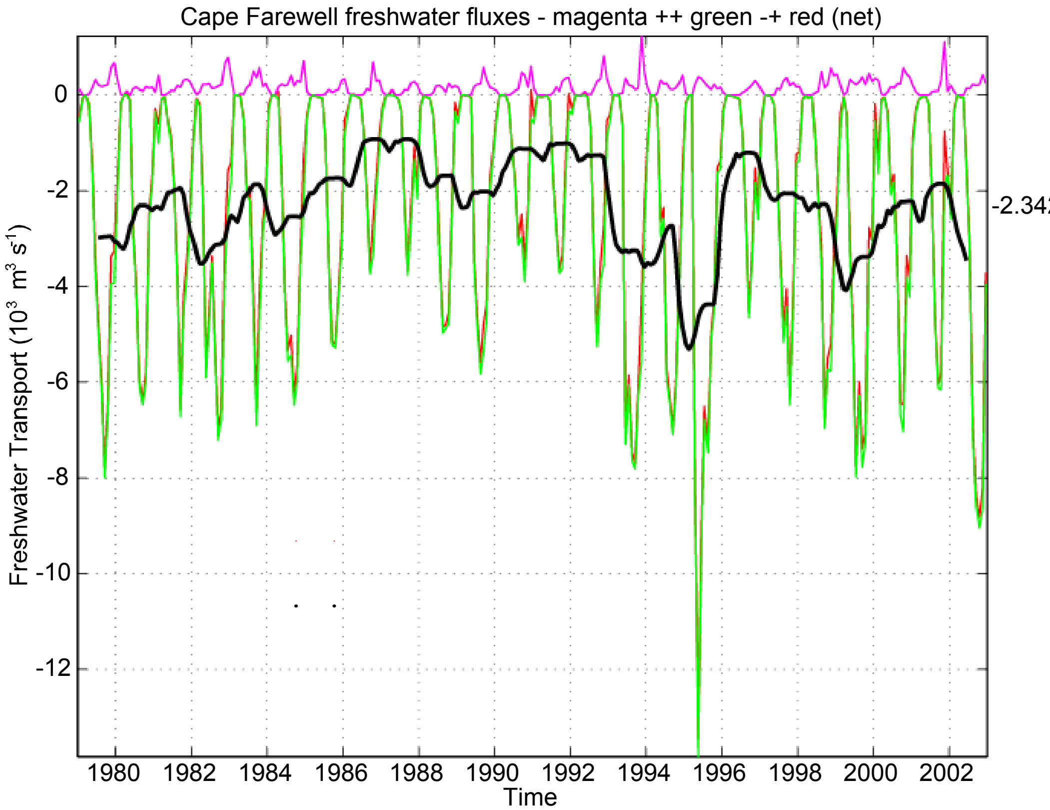

Figure 3.23   1979-2002 monthly mean total freshwater flux through the Cape Farewell minimum flux occurred in 1987 and maximum in 1999.   Negative flux corresponds to flow out of the Arctic. Water less than 34.8 psu into the Arctic (magenta) water less than 34.8 psu out of the Arctic (green) net flow of water (red) and 13-month running mean (black).

In examining the freshwater equivalent flux of sea ice transport through these three sections there was a good correspondence between sea ice freshwater flux and liquid freshwater flux. At Fram Strait the minimum sea ice freshwater occurred in 1985 with a value of about 0.03 Sv(30 mSv) (Figure 3.24),which is about the same time the lowest flux of liquid freshwater was seen at the Fram Strait (Figure 3.20). However, the maximum values in the sea ice freshwater flux occurred slightly earlier in 1994-1995 than in the liquid phase, occurring in 1997. It is

worth noting though, that there was another maximum in the liquid freshwater flux in 1994-1995, which according to monthly mean values was actually higher than the maximum in 1997.

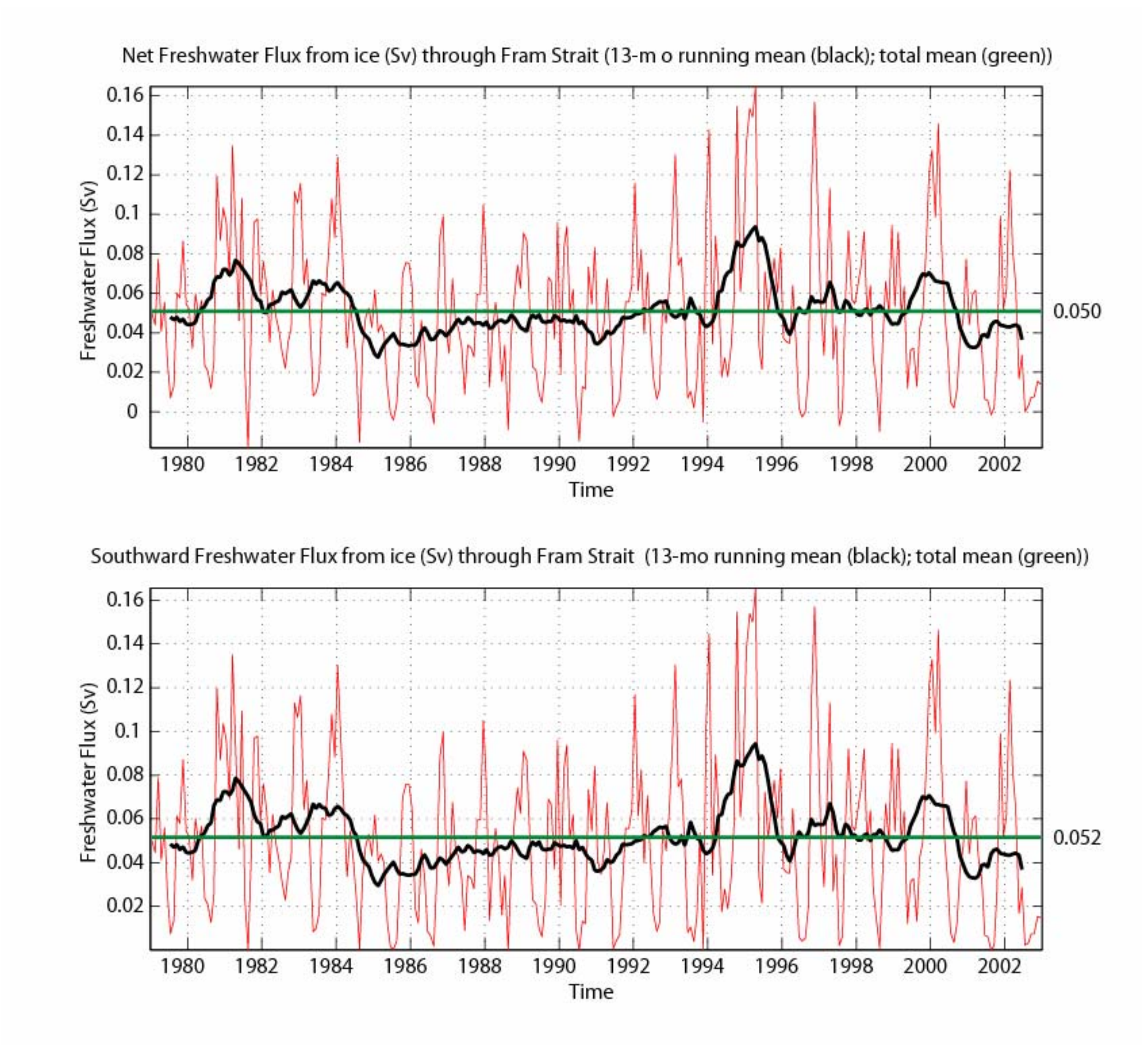

Figure 3.24 1979-2002 monthly mean freshwater equivalent of sea ice flux through the Fram Strait. Positive values represent a southward flux.

A similar relationship is also found in the Denmark Strait with the minimum sea ice freshwater flux occurring

in both the liquid and solid phases in 1987 but with the maximum solid phase occurring slightly earlier in 1995 (Figure 3.25) vice 1999 for the liquid freshwater (Figure 3.22). These results suggest that variability of sea ice transport (in terms of freshwater equivalent) is forced simultaneously by a large weather system, whereas the (liquid) freshwater flux signal is primarily advected downstream from the Fram Strait to the Denmark Strait.

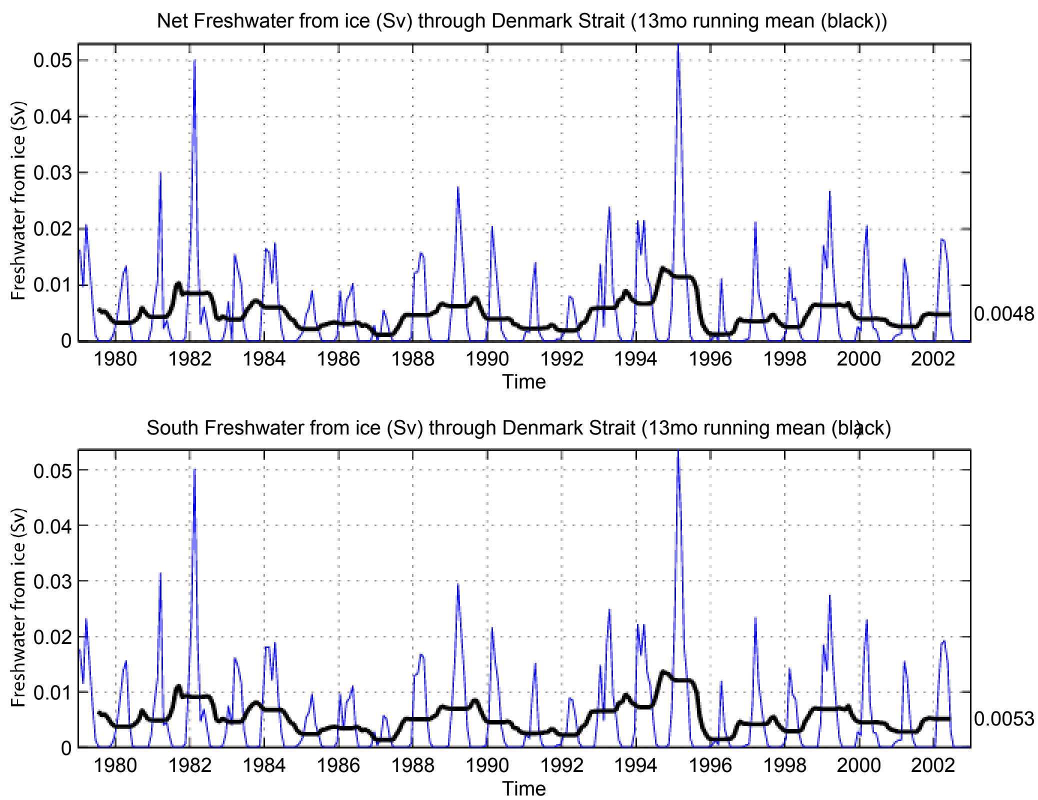

Figure 3.25 1979-2002 monthly mean freshwater equivalent of sea ice flux through the Denmark Strait. Positive values represent a southward flux.

However, these relationships do not hold true for Cape Farewell. Its maximum sea ice freshwater flux actually occurred in the late 1995 (Figure 3.26), which is about the same time its liquid freshwater maximum happened (Figure

3.23). Its minimum values did not occur at the same time as in the Fram and Denmark Straits, but rather the sea ice freshwater occurred before the liquid freshwater minimum.

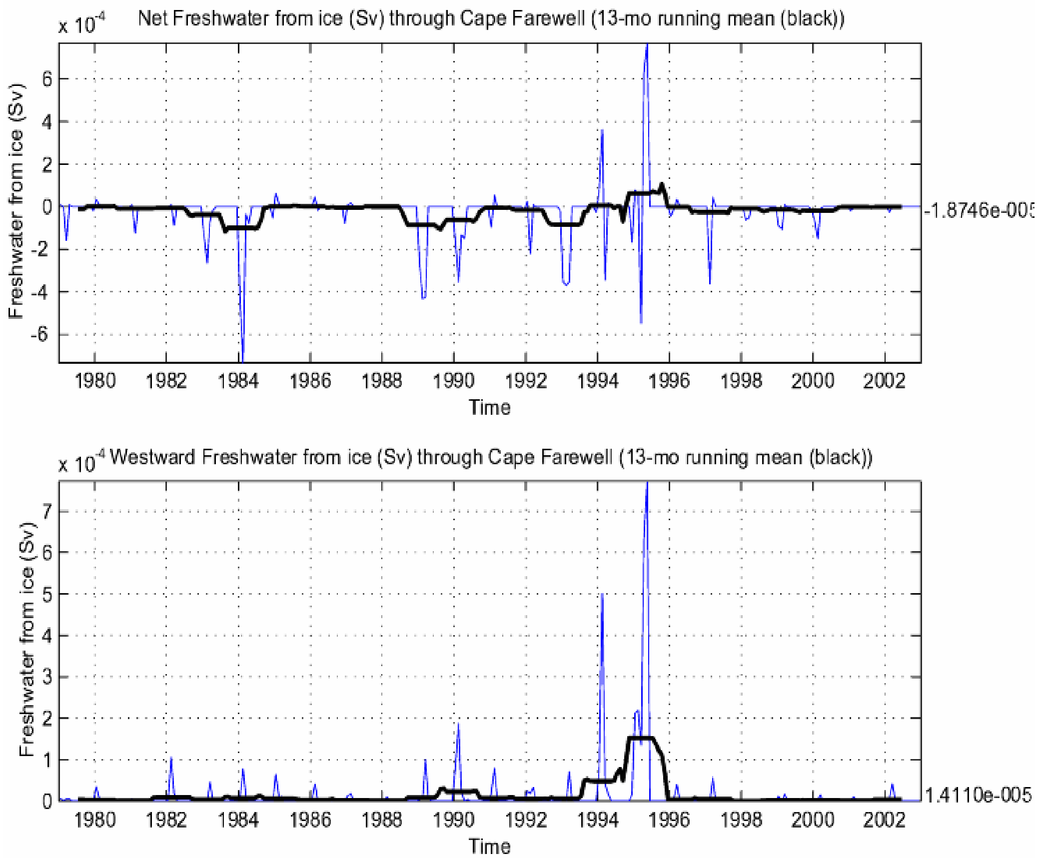

Figure 3.26 1979-2002 monthly mean freshwater equivalent of sea ice flux through Cape Farewell. Maximum flux occurred in 1995.

In the Fram Strait more freshwater was transported in solid phase (sea ice) than in liquid phase by the East Greenland Current. The 24-year mean sea ice freshwater flux was 0.0516 Sv (51.6 mSv), and the liquid freshwater flux only 0.001063 Sv (10.63 mSv), which shows the freshwater from sea ice to be ~ 5 times larger than the liquid freshwater. The sea ice freshwater flux for southerly flow (0.052 Sv or 52 mSv) is also larger than its

southerly liquid freshwater flux (0.001616 Sv or 16.16 mSv). The importance of sea ice is reduced downstream, due to melting caused by atmospheric conditions and relatively warm North Atlantic water re-circulating in the GIN Sea. This effect was seen in the Denmark Strait where the sea ice freshwater flux decreased to 0.00483 Sv (4.83 mSv) an order of magnitude less than in the Fram Strait (0.0516 Sv). Correspondingly, the net liquid freshwater flux for the Denmark Strait increased to 0.00114 Sv (11.42 mSv) compared to the Fram Strait's 0.00106 Sv (10.63 mSv). Furthermore, the reduction in sea ice continued to the section off Cape Farewell where the sea ice freshwater equivalent diminished to 0.0000187 Sv. However, the freshwater liquid flux decreased as well (0.00025 Sv) (2.5 mSv). This is because of the mixing along the East Greenland Current with warm, saline North Atlantic water in the Irminger Sea.

Analysis of the annual cycles of the net and southerly freshwater fluxes for the Fram Strait and the Denmark Strait clearly shows that fluctuations in the Fram Strait were carried downstream. It is also important to note that each section shows good agreement between their respective net and southerly annual freshwater fluxes. The 24-year mean annual cycle of net freshwater flux at Fram Strait experienced a maximum monthly total freshwater flux of 17 mSv in September, and a minimum of 5.8 mSv in May (Figure 3.27).

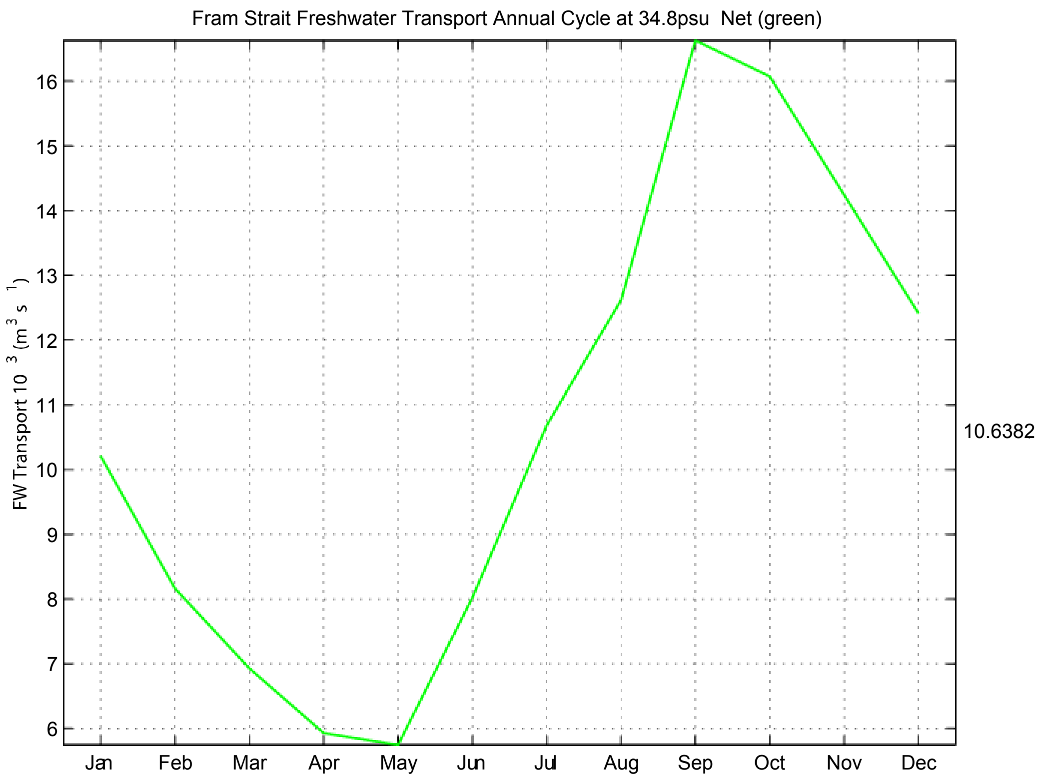

Figure 3.27 24-year mean annual cycle of the net freshwater flux (mSv) through the Fram Strait.

Likewise in the mean annual cycle of southward freshwater flux maximum value was 25 mSv in September and a minimum of 9 mSv in April and May (Figure 3.28).

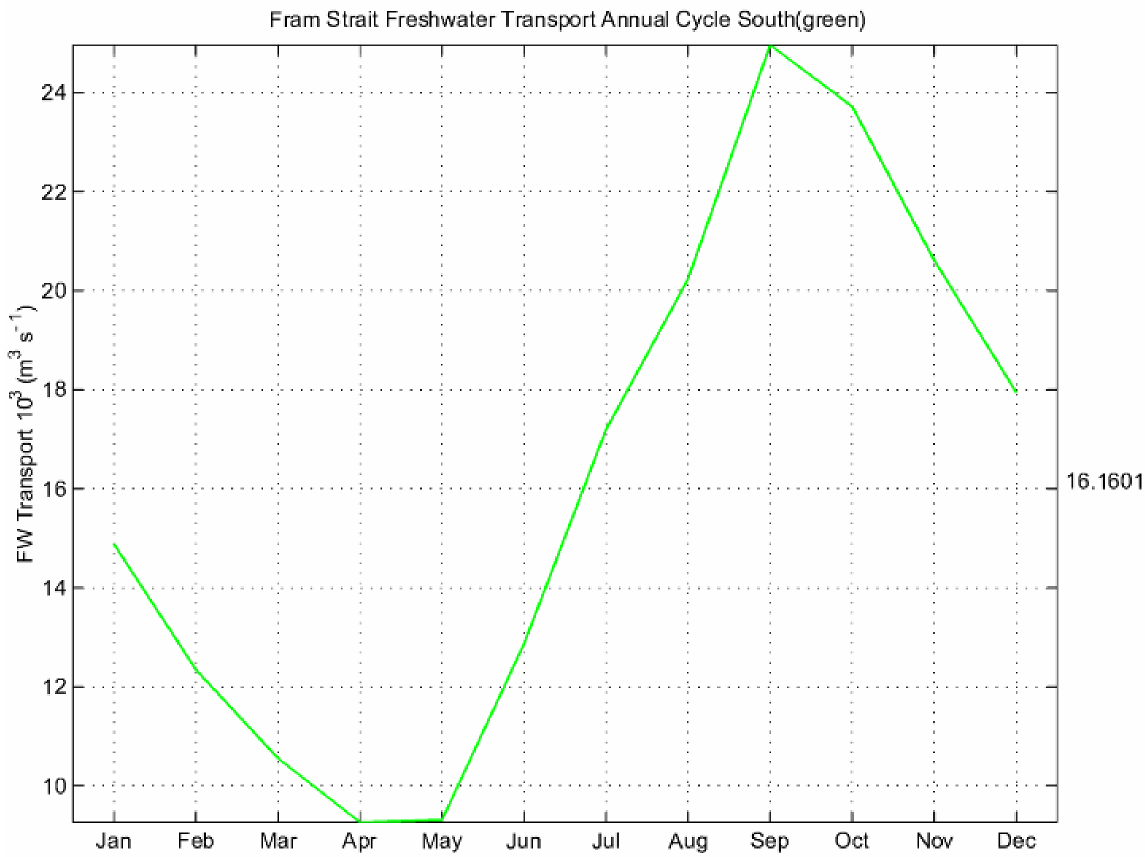

Figure 3.28 24-year mean annual cycle of the southerly freshwater flux (mSv) through the Fram Strait.

The maximum net mean annual cycle appeared one month later in the Denmark Strait in October and the minimum in May (Figure 3.29). Both straits have maxima in fall, which corresponds to a summer sea ice melt in the Arctic and Nordic Seas, with a time delay due to the extent of summer sea ice melt between the two straits. Both straits also had a minimum in the spring, corresponding to the maximum sea ice coverage and the minimum melt in the Arctic Ocean and its marginal seas.

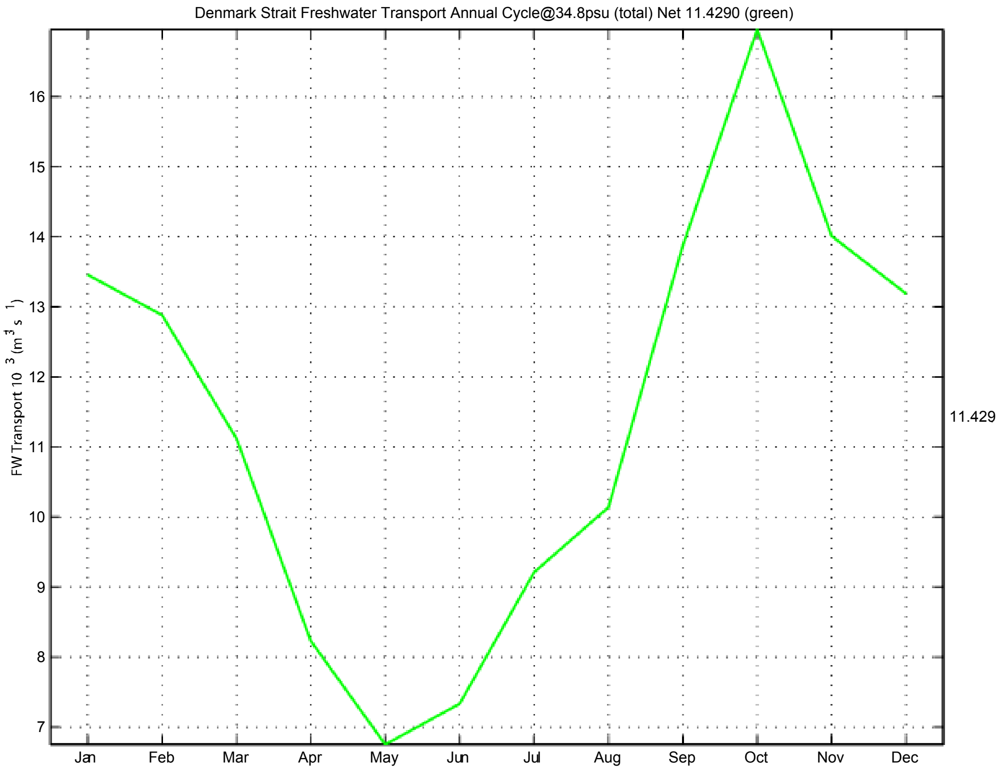

Figure 3.29 24-year mean annual cycle of the net freshwater flux (mSv) through the Denmark Strait.

However, the Cape Farewell section has a maximum in September and a minimum in March (Figure 3.30), which is probably due to the increased importance of mixing within the East Greenland Current with other water masses in the region.

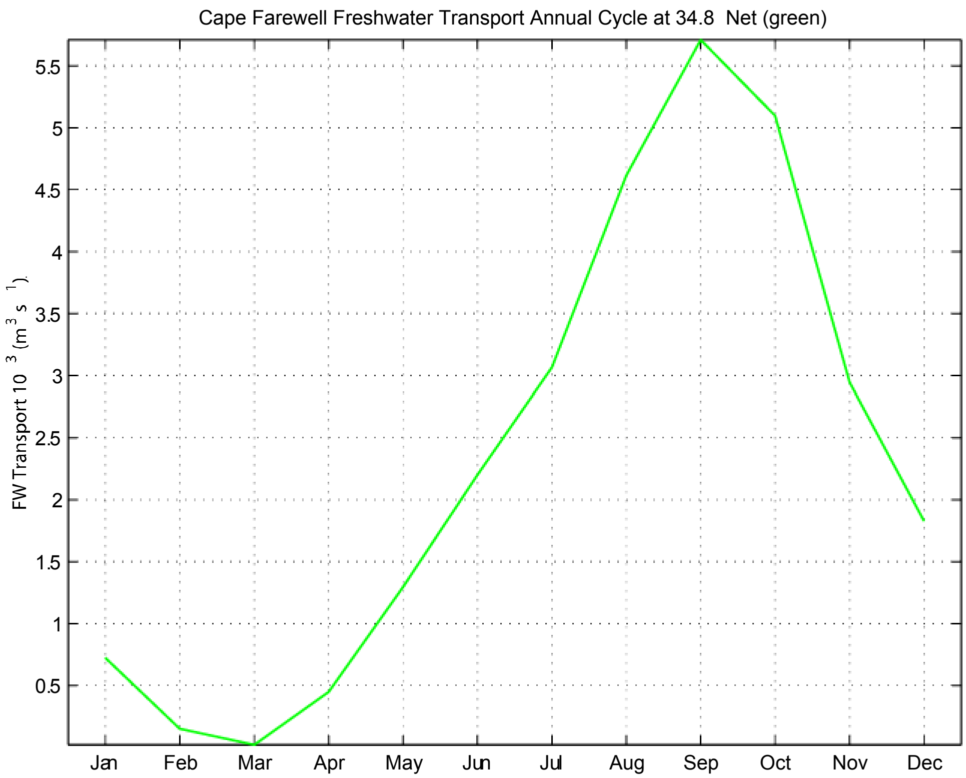

Figure 3.30 24-year mean annual cycle of the net freshwater flux (mSv) through the Cape Farewell Strait.

C. HUDSON BAY

The Foxe/Hecla Strait is a narrow and shallow passage connecting the northern CAA to the Hudson Bay. It acts as the Hudson Bay's only connection to the north, in addition to its entrance into the Labrador Sea via Hudson Strait. Therefore, the flow through Foxe/Hecla is a major contributor to the salinity and temperature fields of the Hudson Bay. It is important to quantify the Hudson Bay freshwater export into the Labrador Sea because of possible affects upon convection in the Labrador Sea. The Foxe/Hecla passage is about 50m deep and is shown (Figure 3.31) to have a completely south-east flow regime. The surface layers are warmer and fresher than the underlying

layers, although the whole water column is relatively fresh with salinity varying from 31.5 at the surface to 32.7 psu at depth and respective temperatures from -0.9C to -1.6C (Figure 3.31).

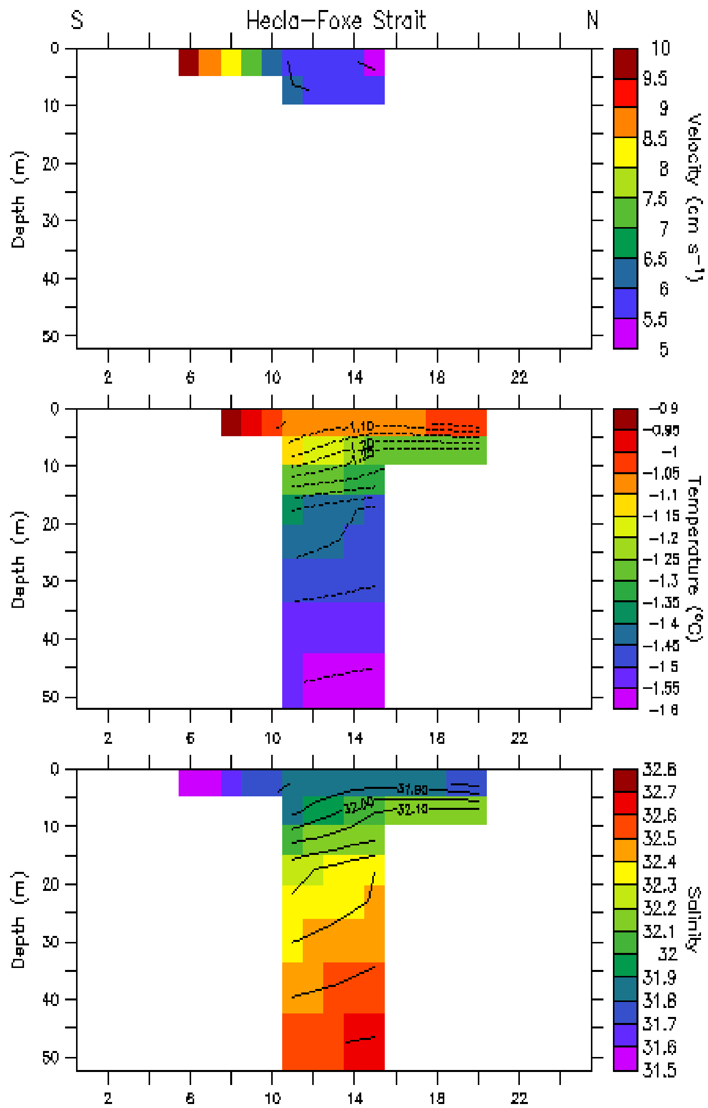

Figure 3.31 24-year average annual velocity, temperature, and salinity profiles for the Foxe/Hecla Strait with positive velocity representing flow away from the Arctic Ocean.

The 24-year mean net volume flux is 0.0261 Sv (Figure 3.32) and the freshwater flux is 2.2442 mSv (Figure 3.33). It reaches a maximum of the mean annual cycle freshwater

flux at 4.5 mSv in August and a minimum of 1 mSv in January, see Table 3.3. This mean variability is similar to that at other passages through the CAA, which also experience maximum flux in August. But there is a time lag of about one month from when the minimum monthly annual cycle flux occurs in the northern CAA in December and when it does in the Foxe/Hecla Strait in January. This is due to the location of the strait further downstream. This implies that the Hudson Bay is at least in part directly affected by changes in the CAA and therefore by changes in the Arctic Ocean.

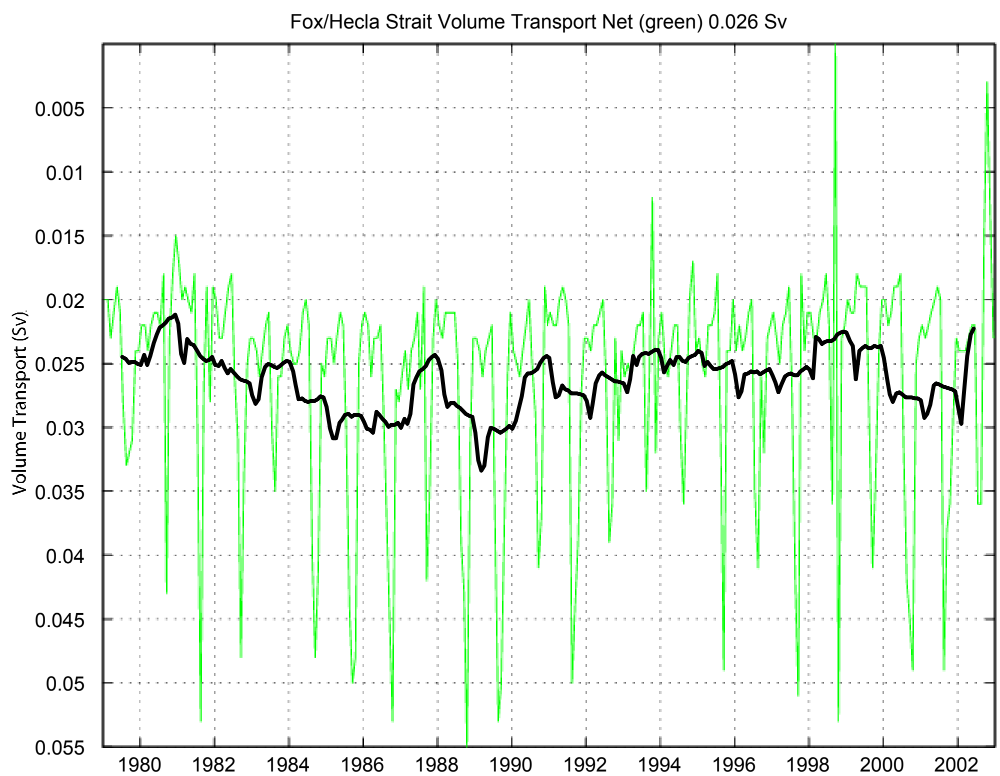

Figure 3.32 1979-2002 net monthly mean (green) and 13-month running mean volume fluxes through the Fox/Hecla Strait.

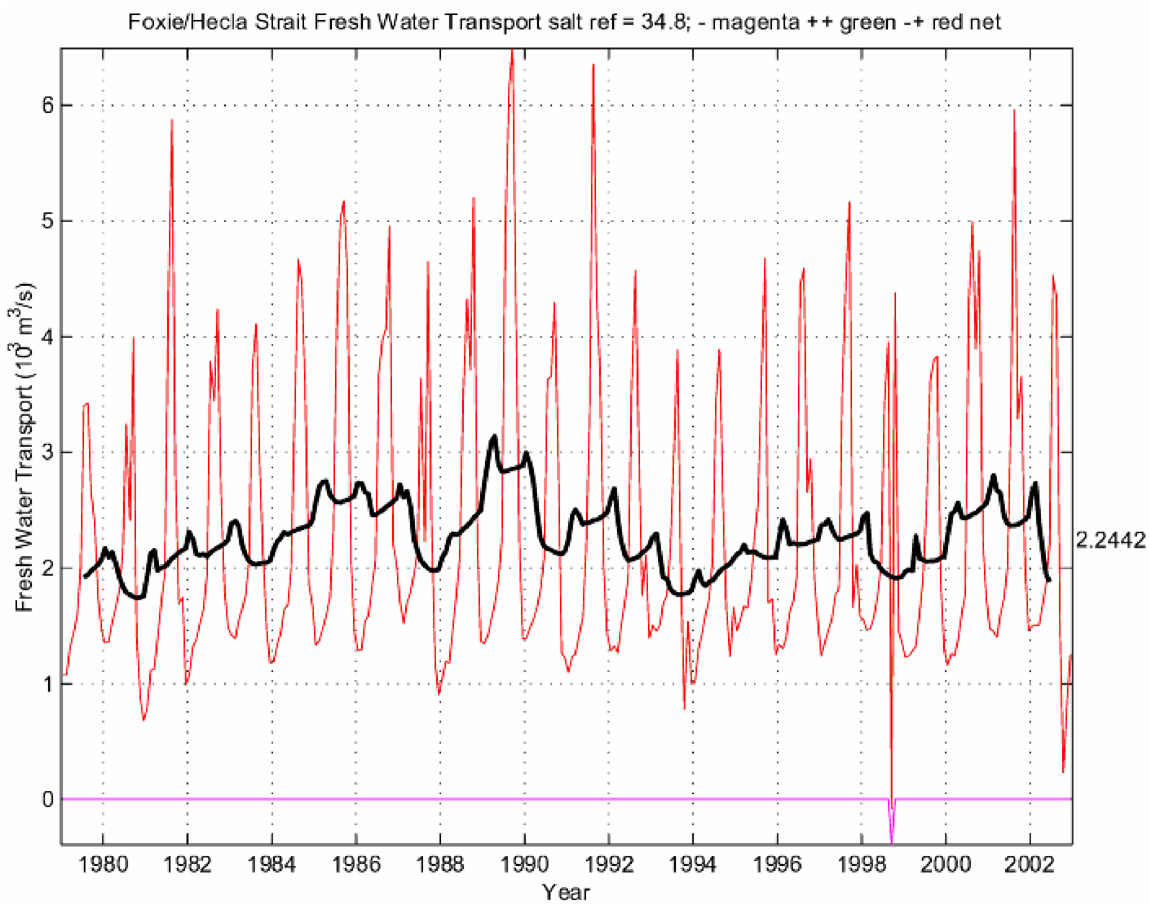

Figure 3.33 1979-2002 monthly mean freshwater fluxes (mSv) through the Foxe/Hecla Strait.

The Hudson Strait transect was taken across the section lying between the Bay and mouth of the Bay into the Labrador Sea, to minimize the effects of recirculation in the Hudson Strait. The 325-m deep transect shows a relatively fast eastward moving surface layer of water, especially on the southern side of the cross-section (Figure 3.34). This layer, about 50m thick, carries fresh and relatively cold water out of the Hudson Bay. Below this depth the flow is westward but very slow, with average speeds of about 0.5cm/s and little over 1 cm/s at the core

located on the northern side between 50m and 100m depth. The eastward upper layer current is of particular importance because of its implications upon the upper ocean salinity in the Labrador Sea. The Hudson Bay acts as an estuary where ambient water (coming at depth through Hudson Strait from the northern Labrador Sea) is mixed with the freshwater entering via Foxe/Hecla Strait from the CAA (and river runoff which is accounted in the model only through the surface restoring to monthly salinity climatology). This results in much fresher water being exported into the Labrador Sea. However, the Hudson Strait transect varied with salinity values 30 psu -34.5 psu, so all the water was considered “fresh” water relative to the reference salinity of 34.8.

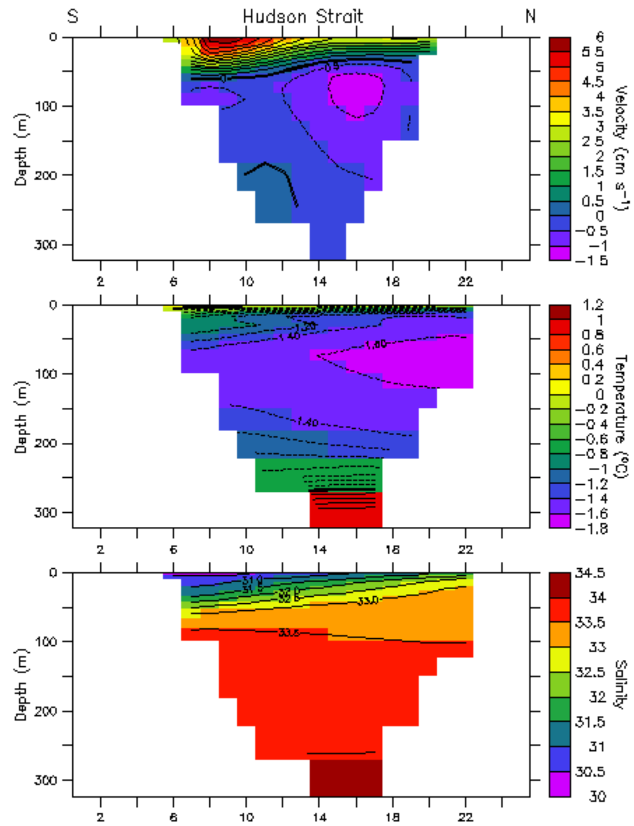

Figure 3.34   24-year average annual velocity, temperature, and salinity profiles for the Hudson Strait with negative velocity indicates flow into the Hudson Bay.

Based on the constructed 24-year mean annual cycle, the maximum annual freshwater export occurs in November with ~22 mSv, with a relative maximum in August and September of 14 mSv, and relatively high values in January (Figure 3.35). The minimum occurs in May at 3.8 mSv indicating a relatively large range of freshwater flux variability for the section. It is worth to note that the maximum freshwater flux in August was similar to the maximum fluxes in other parts of the CAA (e.g. the McClure Strait, Byam Martin Strait, Penny Strait, Foxe/Hecla

Strait, and the Lancaster Sound, see Table 3.3). Yet, the August/September maximum is only relative because the largest mean annual freshwater flux occurred in November. The possible reason for this will be addressed in the discussion.

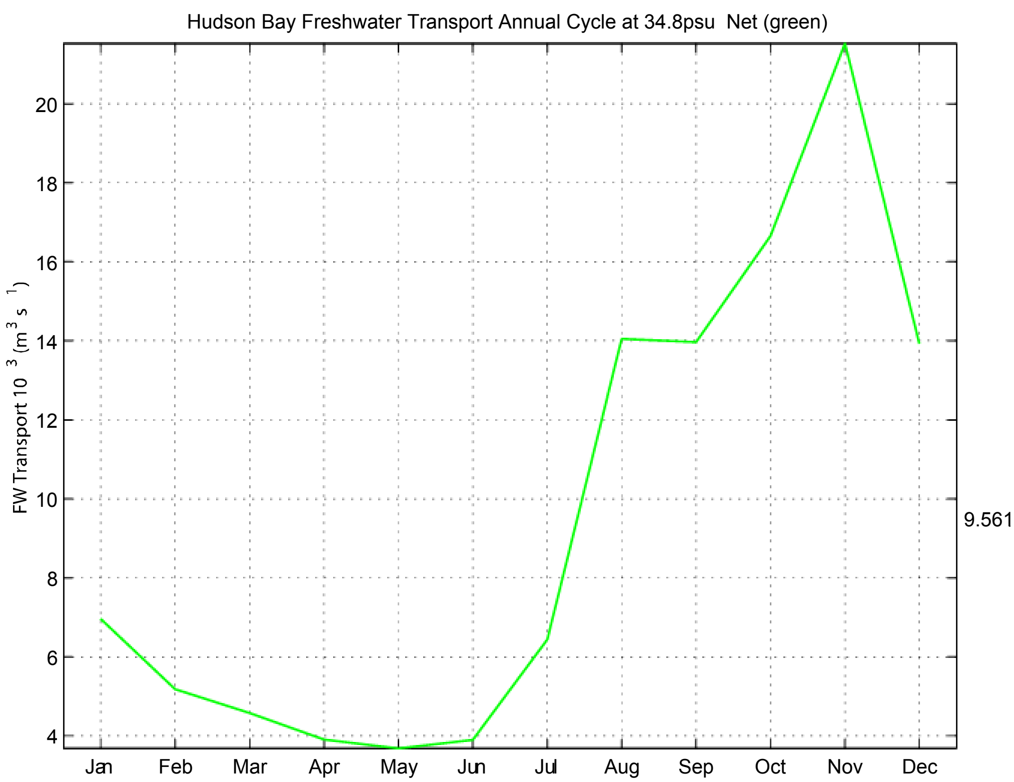

Figure 3.35 24-year mean annual cycle of the net freshwater flux (mSv) through the Hudson Strait.

Another important observation is that the 24-year mean freshwater flux out of the Hudson Bay of 9.561 Sv is almost four times more than that contributed by the water flowing westward across the Cape Farewell section, which provided 2.513 mSv. The consequences and ramifications of this will follow later in the discussion.

Finally, comparison of the maximum and minimum freshwater fluxes during the 24-year time period for the

Hudson and Foxe/Hecla Straits to the other sections of the CAA suggests that variations in sections further north could be propagated south. The maximum freshwater flux for the Hudson Strait (based on the 13-month running mean) occurred in 1991, shown in (Figure 3.36). This is two years after the maximum was observed in the Foxe/Hecla Strait (Figure 3.33) in 1989 and further north in Byam Martin Strait in 1989 (Table 3.2). The propagation of the minimum signal is less convincing as the minimum in the Hudson Strait was in 1998, which was five years after a relative minimum flux in the Foxe/Hecla Strait. Also, the minimum flux in the Hudson Strait in 1998 occurred slightly earlier than the 1999 minimum flux in Jones Strait, McClure Strait, Lancaster Sound, and the Davis Strait.

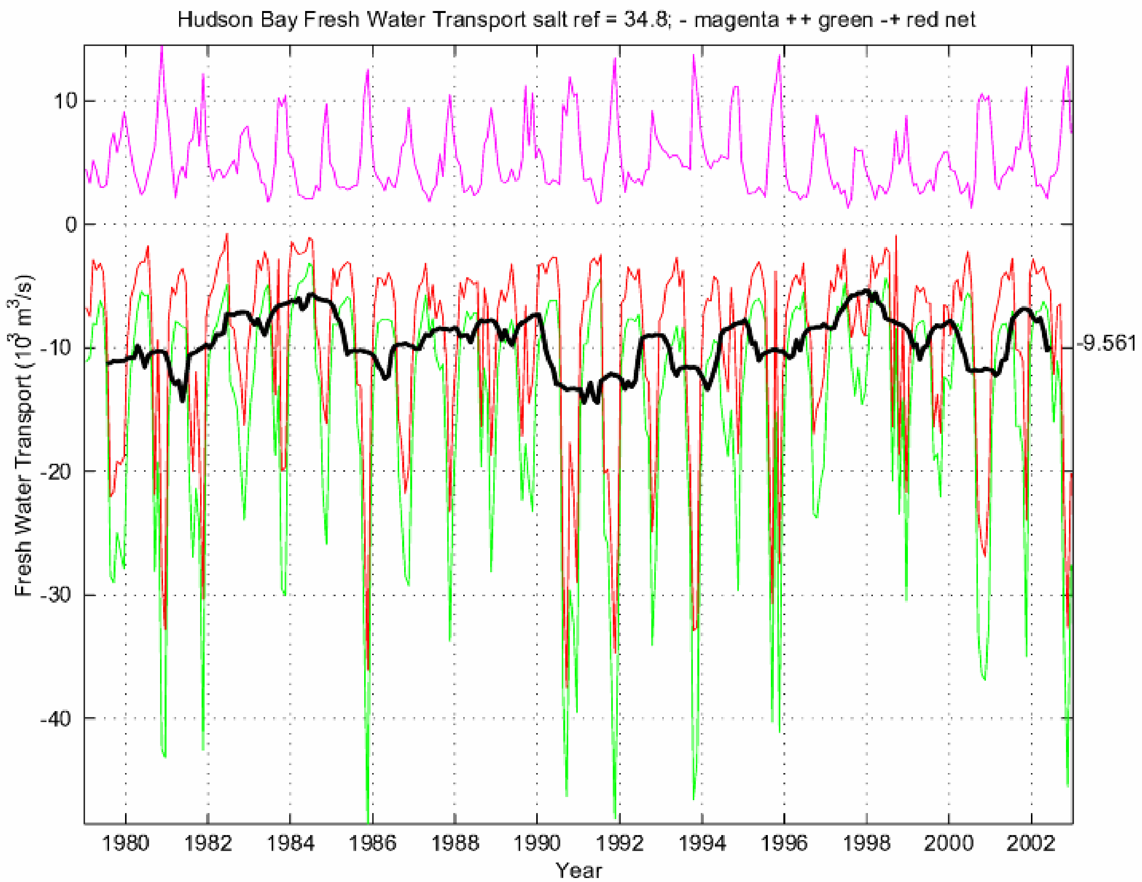

Figure 3.36 1979-2002 monthly mean freshwater fluxes (mSv) through the Hudson Strait. Negative flux corresponds to flow out of the Hudson Bay. The magenta line indicates flow of water less saline than 34.8 psu into the Hudson Bay. The green line indicates flow of water less than 34.8 psu out of the Hudson Bay. The red line indicates the net flow of water and the black line shows the 13-month running mean.

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IV. DISCUSSION

A. CANADIAN ARCTIC ARCHIPELAGO

1. Circulation

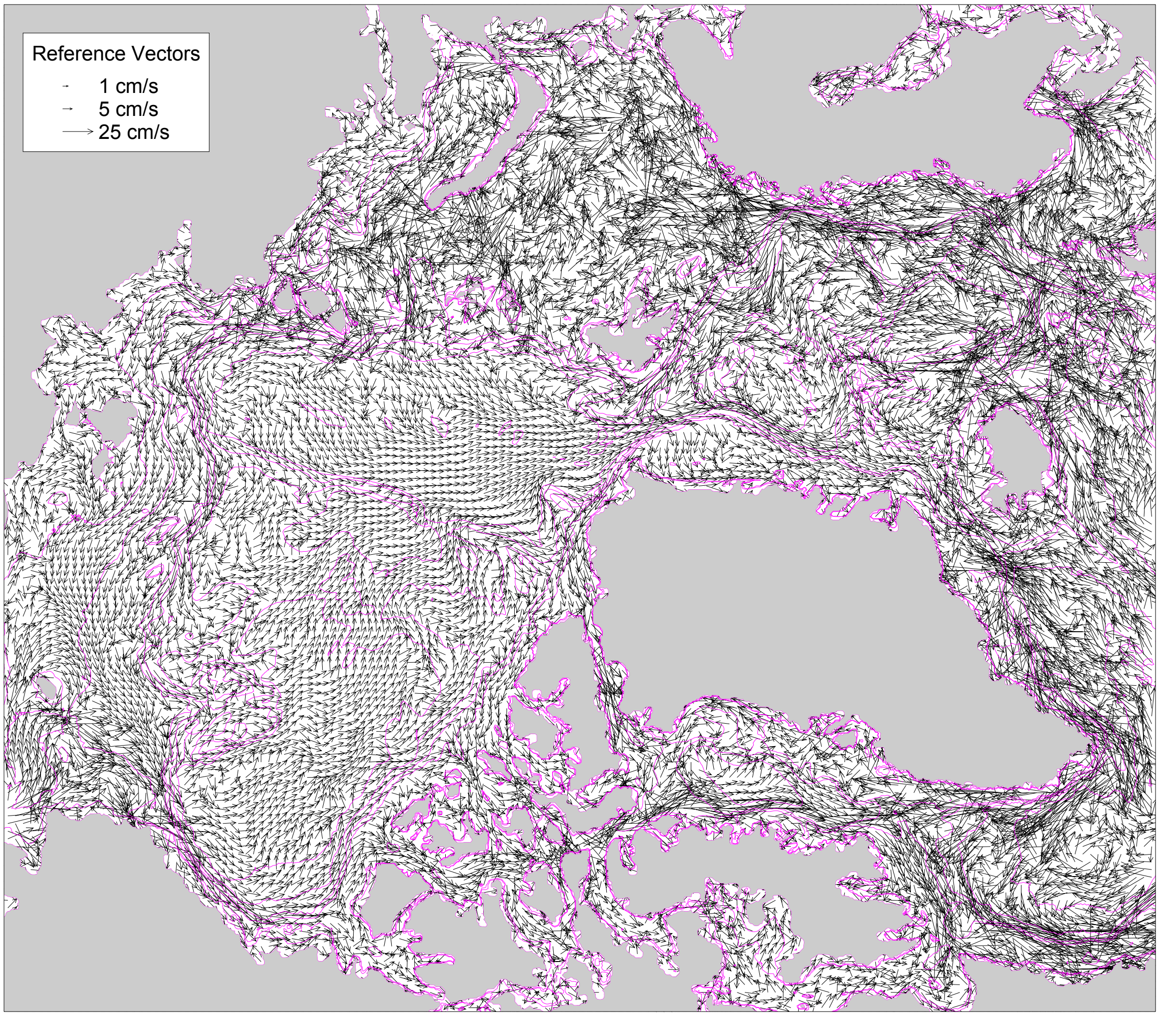

Figure 4.1 24-year mean circulation pattern averaged over the top 100m depth for the Arctic Ocean.

The 24-year mean upper ocean (0-100 m) circulation in the Canadian Basin is mostly cyclonic based upon the analyzed model output. It is hypothesized that the two different circulation regimes, anti-cyclonic and cyclonic, which are dependent upon the dominant atmospheric regime in the Arctic (Proshutinsky et al. 2002), will result in the

Canadian Basin export of different water masses through various passages of the CAA. The following discussion is provided in support of it.

A distinct difference is modeled between the western and eastern straits in the CAA, which receive water due to an anti-cyclonic or cyclonic movement of water to the north of the CAA. The analyzed heat and freshwater fluxes tend to support this hypothesis. The largest differences in the mean annual heat and freshwater fluxes can be seen between the western most section, McClure Strait, and the eastern most section, Robeson Strait. McClure Strait receives most of its water from the eastward flow over the shelf and slope in the Western Canadian Basin (Figure 4.1). The water entering the CAA at this point must flow over shallow sills therefore enabling only the surface waters to enter the McClure Strait (Melling et al., 1984). These surface waters are fresh and cold because they still retain influences from the fresher inflows from the Bering Strait and the Pacific Ocean (Melling et al., 1984). This influence can be seen in the heat flux values through the McClure Strait. In Figure 4.2 the total heat flux is shown as a product of temperature difference referenced to temperature of -0.1 $^{\circ}$C and velocity. It is clear that the dominant heat flux is positive (i.e. water colder than the reference temperature moving southward). This supports the idea that cold surface waters are being moved out of the Western Canadian Basin cyclonically.

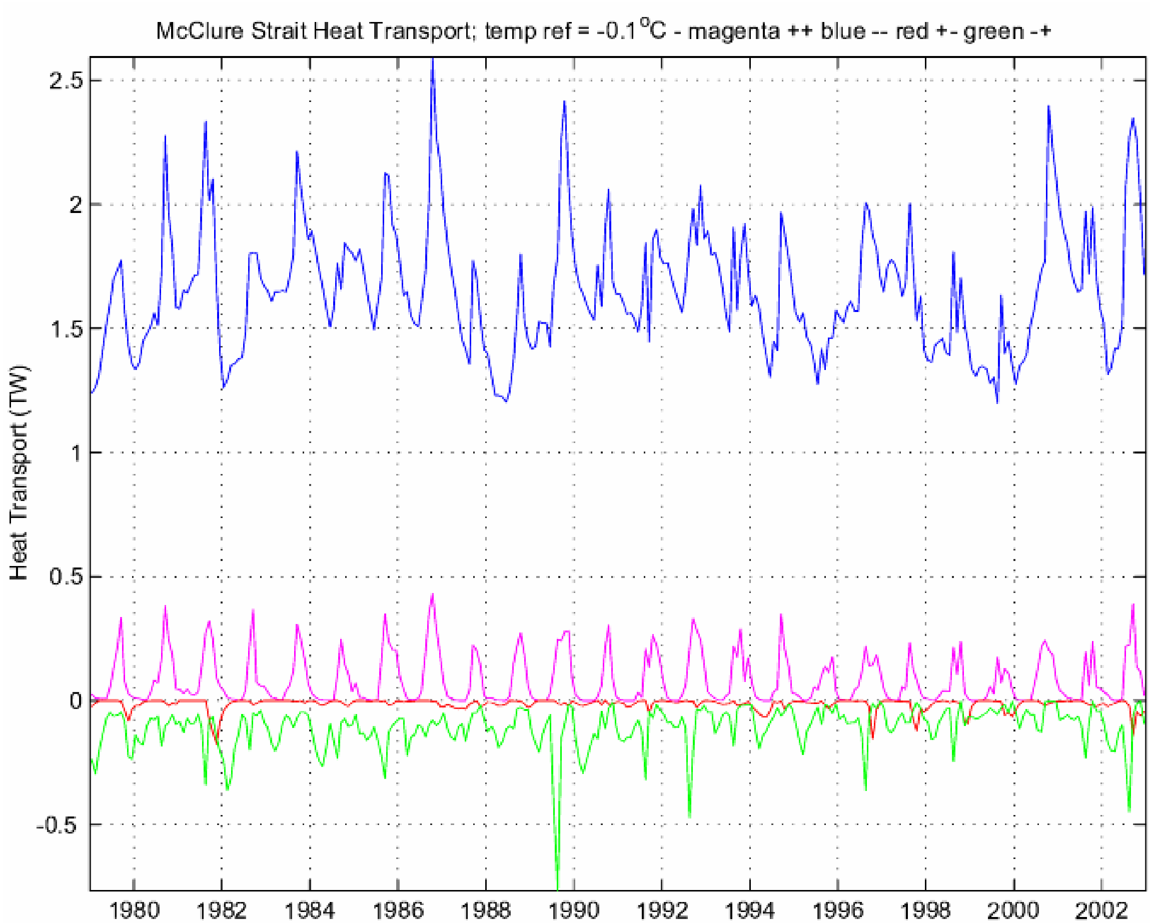

Figure 4.2 1979-2002 monthly mean heat flux for the McClure Strait. The magenta line indicates warmer water moving north into the Arctic Ocean. The blue line indicates colder than -0.1 °C water moving out of the Arctic into the Baffin Bay. The red line indicates colder than -0.1 °C water moving into the Arctic and the green line indicates warmer than -0.1 °C water moving out of the Arctic.

The Robeson Strait is the easternmost section of all the analyzed sections in the CAA, which makes it the first pathway to be affected by westward or anti-cyclonic circulation, associated with the entrance into this strait. The analysis of the heat flux for this strait (Figure 3.11), and for the more southerly section of Smith Strait

(Figure 3.12) show a strong southerly flow of warmer (greater than -0.1 ^{o}C) water.

Also comparing the 24-year averaged salinity cross-sections for Robeson Strait (Figure 3.4) and McClure Strait (Figure 3.2) shows that Robeson Strait is more saline (with surface salinities of 33.0) than McClure (with surface salinities below 32.0). This supports the idea of two different flow regimes in the Arctic influencing the inflows into the CAA. An anti-cyclonic flow would bring warmer and saltier water from the east, possibly from the eastern parts of the Central Arctic Ocean or even from the Eurasian Basin, where surface salinity values are generally greater than those found in the Canadian Basin (Boyd and Steele, 1998). The cyclonic flow would bring fresher and colder surface waters east due to input from the Bering Sea, which is freshened by the incoming Alaska Coastal Current (Schumacher et al., 1989) and local river runoff. Another possible source of the fresh, cold water could be from the net sea ice melt along the Chukchi slope region (Dixon, 2003).

The influence of the Arctic Ocean's circulation regime affects when certain straits in the CAA experience maximum and minimum freshwater fluxes throughout the year. The Robeson Strait's 24-year maximum freshwater flux occurs in August and the minimum in October (Figure 3.14). This is most likely in response to local sea ice melt and formation in and north of the Robeson Strait. However, the strait also shows a distinctive relative maximum in March, which is when the Robeson Strait is still covered with sea ice. A maximum freshwater flux appears in the Smith Strait in February (Figure 3.15), which is also a month when the strait is ice covered. Another relative maximum at this

strait in August is very close in value to the absolute maximum. The Smith Strait’s minimum freshwater flux coincides with Robeson Strait and occurs also in October. Another unanticipated point is the relative minimum flux seen in both sections in June, a time when the area is often ice free.

Similarly, there is also a relative maximum freshwater flux in the Penny Strait (lying to the west) in March (Figure 3.16) but it is not as pronounced as the maximum in the Robeson Strait. The Penny Strait also has a still recognizable relative minimum in June. Continuing further west, there is no distinct relative maximum freshwater flux in the Byam Martin Strait, instead there is a gradual increase in freshwater flux in the spring months, when the region is ice covered (Figure 3.17). The month of June in this section is the transition month between a gradual increase in the freshwater during the spring months to an accelerated rate of freshwater export in the summer season. However, looking at the most western strait in the CAA, the McClure Strait, there is no indication of any additional freshwater source entering in the spring season, but rather minimum freshwater fluxes are shown (Figure 4.6).

The declining strength of relative spring maxima of freshwater fluxes supports the possibility of a delayed propagation of sea ice melt water and runoff signals traveling anti-cyclonically around the Central Arctic. The timing of the relative maximum flux appearing in Robeson Strait in March corresponds to a six-month time lag behind a typical maximum summer sea ice melt in the central Arctic, in September. This six-month time lag can also again help explain the relative minimum freshwater flux in

June, occurring about six months after the intense sea ice formation in the central Arctic Ocean occurring in winter.

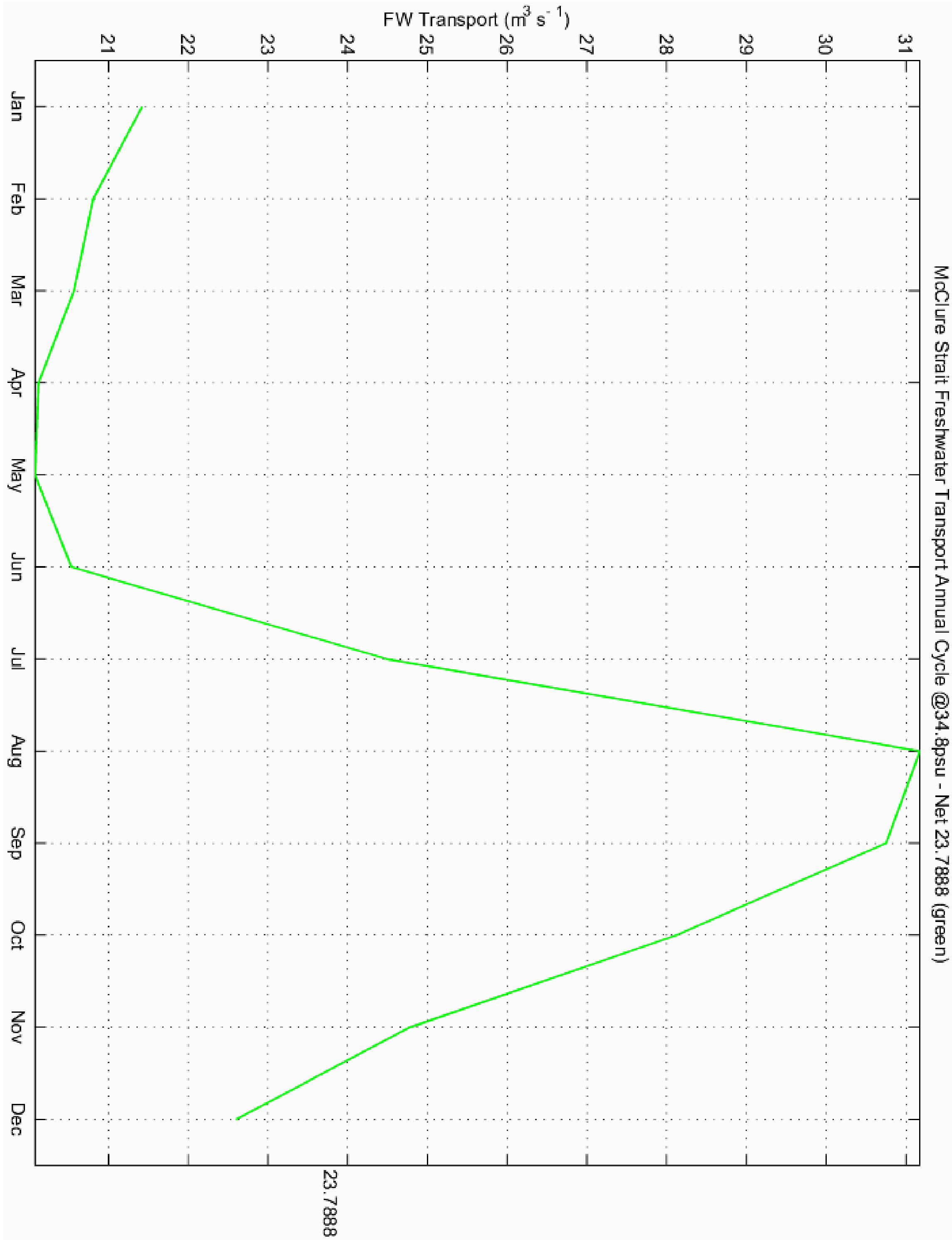

Figure 4.6 24-year monthly mean freshwater fluxes through the McClure Strait.

2. Annual Mean Volume and Freshwater Fluxes

The annual mean extreme volume and freshwater fluxes occurred at approximately the same time. The majority of the minima and relative minima in volume fluxes of the sections occurred in 1980-1981 and 1999 respectively. These results have good agreement with the minima and relative minima annual freshwater fluxes which experienced either relative or absolute minimal fluxes during these times. The maximum volume flux occurred in the majority of the sections in the CAA between 1990 and 1991 (Table 3.1), which also corresponds to the maximum freshwater flux through most of the sections in 1990 (Table 3.2). These results are consistent with those found by Dickson et al. (2002), who reported the freshest and coldest water appearing in the Labrador Sea in the early 1990's. The above agreement implies that the freshwater flux through the CAA depends upon the volume flux out of the Arctic Ocean. Also, the majority of the sections experienced maximum or minimum fluxes at approximately the same time ,which supports the idea of continuous flow through the CAA with small residence time. This becomes especially important if there continues to be an increased export of freshwater from the Arctic Ocean because it suggests freshwater entering through the CAA passages could quickly pass through and affect convection in the Labrador Sea.

The notion of short residence time for freshwater flowing through the CAA is further supported by analyzes of the mean annual flux from: Smith, Jones, and Lancaster Sounds, to the Davis Strait, further downstream. The maximum freshwater fluxes through these four straits occur within 1-2 months of each other during the melt season. However, the time lag between these sections increases to

3-5 months during the winter months when the minimum fluxes occur. The reduced time lag between sections during episodes of increased freshwater export through the CAA compared against freshwater export via the Fram Strait supports the notion of freshwater from the Arctic being transported into the Labrador Sea sooner than previously suspected.

In the Hudson Strait two relative maxima of freshwater flux appeared in August and September (Figure 3.35) which can be explained by local seasonal sea ice melt. It also coincides with maximum freshwater fluxes in the northern CAA, which means the Hudson Strait, like the other sections in the CAA must be affected by the melt water forced freshwater export from the Arctic Ocean. However, the absolute maximum flux in November was unexpected because it occurred when most of the area was ice covered. But, the results agree with LeBlond et al.(1996), who claimed the Hudson Strait experiences its minimum salinity value in November/December due to a six-month time delay between maximum river runoff into the central Hudson Bay, in May and June. By the same argument, the minimum freshwater flux in April and May in the Hudson Strait could possibly be a six month time delay from the melt season in the central Hudson Bay during the summer months.

The Hudson Strait’s 24-year time series of freshwater flux showed a maximum in 1991, two years after the maximum freshwater flux passed through the Foxe/Hecla Strait. The minimum however had a longer lag time of four years before the signal was propagated from the Foxe/Hecla Strait to the Hudson Strait. Again this suggests that increased freshwater flux levels from the Arctic could be transported

to the Labrador Sea more quickly than previously anticipated.

B. MODEL VERIFICATION

The sections used in this study were chosen in order to capture all the water leaving from the Arctic Ocean and entering into the Baffin Bay and the Labrador Sea. In this way the flow through the straits and the two main pathways could be quantified relative to each. The sum of average annual volume fluxes through the northern straits: McClure Strait, Byam Martin Strait, Dease Strait, and Penny Strait with the volume flux of Foxe/Hecla Strait, amounts to 0.758 Sv. This agrees with the model's volume flux through the Lancaster Sound of 0.759 Sv. The agreement in the volume fluxes is a good verification of the consistency of our calculations throughout the CAA and that all the flow into the CAA was accounted for. The model estimated mean flux through the Northwest Passage, is also supported by observational data by Prinsenburg and Hamilton (2004), who estimated a three-year mean volume flux for the Lancaster Sound at 0.75 Sv.

Additionally, the combined mean flux through the Jones Sound, Lancaster Sound, and Smith Sound into the northern Baffin Bay amounts to 1.552 Sv, which is very close to the volume flow at the Davis Strait, 1.572 Sv. The small difference could be an indication of round off errors or a missed small fraction of the flow due to analysis methods.

The 9-km resolution model was also compared against the earlier 18-km version of this model (Maslowski et al., 2000, Maslowski et al., 2001). In all the sections the 18-km model underestimated the freshwater flow significantly. The 9-km model allows two to twenty times the flux amount

of freshwater reported from the older 18-km model. However, freshwater minimum and maximum fluxes occurred at about the same time in both models. This suggests that the earlier model was able to represent flux variability quite realistically but underestimated the actual amount of freshwater being transported simply due to its insufficient horizontal and vertical resolution.

C. COMMUNICATION BETWEEN THE CAA AND THE FRAM STRAIT

Dixon (2003) reports a dominant cyclonic flow around the Canadian Basin based upon this 9-km model output from 1979-2001. In 1991-1992 the model showed increased intensity of this circulation, in response to a cyclonic atmospheric regime, which intensified in the late 1980’s and peaked in the early 1990’s. These findings can be further supported by examining the present model response of maximum and minimum freshwater fluxes in the CAA and Fram Strait, which are the two pathways for freshwater export from the Canadian Basin.

All of the sections in the CAA experienced maxima or relative maxima in freshwater fluxes between 1989 and 1990, which supports Dixon’s (2003) findings of the model’s intensification of cyclonic flow in the Canadian Basin, which favors the increased flow through the CAA. However, the Fram Strait did not reach its maximum freshwater flux until about 1997 and the Denmark Strait in 1999. This delayed response could be a result of a time lag between freshwater export from the Canadian Basin through the CAA and the Fram Strait, during the cyclonic circulation in the Canadian Basin.

There was a significant minimum annual freshwater flux that was apparent across the CAA in 1981, which was

also shown in the 23-year model analysis of the circulation intensity upstream in the Arctic Ocean conducted by Dixon (2003). The reduced freshwater flux in the CAA around 1981 is in agreement with an increased strength of the so-called Beaufort Gyre in the Canadian Basin at that time. The minimum flux values do not appear in the Fram Strait until 1985-1986, which is four to five years after the minima in the CAA. Again this could be interpreted as a time lag due to the propagation of freshwater from the west to the east. However, further analysis should be conducted to better understand the connection between the large scale circulation in the central Arctic Ocean and the freshwater export through the CAA and Fram Strait.

Minimum freshwater fluxes due to the sea ice export through the Fram and Denmark straits occur at approximately the same time as they appear for liquid freshwater fluxes. However maximum sea ice freshwater fluxes across those straits occur several years earlier than the liquid freshwater fluxes. This supports the notion that sea ice velocities are heavily dependent upon atmospheric conditions like sea level pressure gradients and wind speed (Vinje, 2000). This could result in thicker sea ice being transported south by the more cyclonic winds more quickly than a maximum liquid freshwater flux signal would require to be transported from the central basin by ocean currents. Attention should also be drawn to the fact that Cape Farewell does not follow the same trends as the other two straits because its contribution from sea ice is much less than in the northern sections. In addition, the recirculation of Atlantic water in the Irminger Sea provides an additional (negative) freshwater signal to the flux. Therefore, it is reasonable to expect very little or

no correlation between sea ice and liquid freshwater fluxes at Cape Farewell with those further north.

D. TOTAL FRESHWATER FLUX FOR THE LABRADOR SEA

Three additional sections were constructed to evaluate the total amount of freshwater entering the Labrador Sea from the Baffin and the Hudson Bays. These sections, shown in Figure 2.1, are termed: the Pre-Labrador Section, the Hudson Bay Mouth, and the Labrador Section. The Pre-Labrador Section accounts for the freshwater entering from the northern Baffin Bay via Davis Strait, and from the recirculation of the West Greenland Current. The Hudson Bay Mouth transect represents the freshwater moving out of the Hudson Bay. However, it should be noted that because this section is at the mouth of the Hudson Bay it is subjected to a lot of recirculation. Therefore the Labrador Section freshwater flux is designed to represent all the freshwater that enters the Labrador Sea downstream of Hudson Strait and can be analyzed for its possible impact upon convection.

To test the model's accuracy at accounting for the total freshwater input into the Labrador Sea the contributions of each section's liquid freshwater and sea ice freshwater flux values were added to compare with the total Labrador Sea's freshwater flux. The results show only about 0.4% error between the summed value of 77.7112 mSv from the Hudson Bay and the Pre-Labrador section, and the model's freshwater flux value of 78.0316 mSv for the Labrador Strait. This means that the model accurately accounts for all the freshwater flow into the Labrador Sea.

Results show the Hudson Strait mean flux of 9.561 mSv of liquid freshwater. However, this value is decreased

through mixing with more saline water entering the Hudson Strait from the Labrador Sea, so that at the Hudson's mouth the freshwater flux has decreased to 6.069 mSv, including sea ice. Yet, this number is still ~2.5 times more than the contribution by the freshwater off Cape Farewell (2.253 mSv) with sea ice. Also, the total amount of freshwater, both liquid and from sea ice, from the Hudson Bay Mouth accounts for ~8% of the total freshwater leaving through the Labrador Sea section. This implies that the Hudson Bay provides a significant amount of freshwater into the Labrador Sea, especially compared to the freshwater contribution from Fram Strait.

V. CONCLUSIONS

The CAA provides a direct path for freshwater leaving the Arctic into the Labrador Sea, where it could possibly affect the formation of Labrador Sea Water. The analysis of the 24-year mean annual cycles for the CAA shows relatively similar behavior among the sections with three to six month lag for freshwater fluxes to be propagated between the Northern Baffin Bay and the Davis Strait. Additionally, the maximum and minimum volume and freshwater fluxes for the sections of the CAA also occur at approximately the same time, based on analysis of the 24-year monthly mean time series. This suggests that the residence time for water transiting through the CAA is short. Unlike the longer residence time of a few years, which is seen, for the water flowing between the Fram and Denmark Straits. This stresses the importance of accurate and long-term measurements of volume and freshwater fluxes through the CAA.

The importance of the CAA freshwater contribution to the Labrador Sea and ultimately the North Atlantic has not been sufficiently studied in part due to the focus of most research on the Fram Strait pathway for water and sea ice export into the Nordic Seas and the northern North Atlantic. However, our analyses suggest that the total westward freshwater flux off of Cape Farewell is significantly reduced due to the 'salinification' of the signal along its path. This increases the relative importance of the freshwater contribution from the Canadian Arctic Archipelago. Based on quantitative comparison the freshwater input from the CAA appears to be the most

important freshwater source for the Labrador Sea. This thesis does not necessarily downplay the role of freshwater from the Fram and Denmark Strait, but it serves to distinguish the different roles various water masses play in deep water formation in the sub polar North Atlantic. The 24-year mean total freshwater contribution from both ice and liquid, out of the Denmark Strait in this study is 16.22 mSv and it diminishes to ~2.5 mSv at Cape Farewell, which suggests that the amount will be even less when it reaches the Labrador Sea. Therefore, compared to the total freshwater flux (at the Labrador section) the freshwater flow from the Arctic via the Fram Strait does not have a major impact on convection in the Labrador Sea.

It must also be noted that all the results are based upon the salinity reference of 34.8 psu, so that if water from the Denmark Strait has higher salinity than this value it is considered "salty" water. However, the flow through Denmark Strait lowers the salinity of large amounts of water through its mixing with Atlantic Water along the way into the Labrador Sea. This is different from the freshwater outflow from the CAA, which remains relatively isolated on the northern Labrador shelves (Cuny, et al. 2002). Therefore, the water from the CAA has a low salinity when it reaches the Labrador Sea, which consequently may have a major impact upon convection in the region.

VI. SUMMARY

The 24-year model output was used for analyses of freshwater export from the Arctic Ocean through the Canadian Arctic Archipelago, the Fram and Denmark Straits, and Cape Farewell to understand the circulation regime in these areas and to quantify the flux of freshwater entering the northern North Atlantic. The importance of this study is two-fold: scientific importance and Navy relevance. The scientific importance lies in the determination of the potential role of the CAA through flow on convection in the Labrador Sea, especially in the context of the recent increase of freshwater export via this route. The anomalous melting of sea ice in the Arctic Ocean (Serreze et al., 2003) and continued positive trend in freshwater flux may provide a large buoyancy signal to the North Atlantic with potentially drastic effects upon the global thermohaline circulation and the global climate. The naval relevance lies in the increase of freshwater flux from the Arctic as a result of the reduction of sea ice in the Arctic Ocean and the CAA due to recent warming. This could allow for the opening of new shipping lanes for international commercial and military vessels in the relatively near future. Therefore, the U.S. Navy may sooner than expected need to start planning the response to an increased security threat from rogue nation states and learn how to successfully operate equipment and personnel under new environmental conditions.

The 24-year average mean velocity, temperature, and salinity profiles for each section were constructed to describe the flow regime in each area. These results

showed temporal and spatial variability at various sections and the influence the upstream circulation had on the flow and water mass characteristics. The analysis of the 24-year mean profiles was combined with their 24-year time series plots for volume, heat, and freshwater fluxes. Analysis of this data along with 24-year mean annual of freshwater flux showed when maximum and minimum fluxes occurred and how they propagated throughout the CAA over time.

The combined volume fluxes at several sections were compared with known observational fluxes at the same sections to verify the model's performance. In all considered cases the model accurately accounted for the volume flow through the sections. The model output was also compared against results from an earlier model at 18-km resolution. Similar trends were found but at significantly different magnitudes. It was concluded that the model at 18-km did not have enough resolution to accurately account for all the freshwater flux through the narrow and shallow straits of the CAA.

Several important observations were made from this study. The first showed that the Canadian Arctic Archipelago is the largest freshwater contributor to the Labrador Sea and the Hudson Bay is the second largest. Therefore, the Hudson Bay's freshwater import is more significant than the freshwater exported through the Fram Strait to the Labrador Sea. Also, the freshwater export to the Labrador Sea is directly affected by circulation patterns in the Arctic Ocean, which are subjected to change due to large scale atmospheric forcing. This supports the hypothesis that atmospheric regime shifts in the Arctic

possibly associated with global warming could hinder convection in the Labrador Sea.

A. FUTURE RECOMMENDATIONS

Further research is needed to understand the relationship between freshwater export from the Arctic Ocean to the Fram Strait and the Canadian Arctic Archipelago. Observational data can give good insight into the actual dynamics of the ocean in these regions and would help verify model output. An expansion of the both observational and model time series can provide a valuable insight into long term variability in the Arctic Ocean and aid in predicting future change. Inclusion of tides would also produce more realistic results by accounting for tidal mixing and residual currents. Higher resolution would also allow for small eddies to be explicitly modeled. A more realistic atmospheric forcing at increased resolution would provide improved forcing of ocean circulation and water column parameters.

Additional research is being continued by the Arctic/Sub arctic Ocean Fluxes (ASOF) program with some of the main goals including better understanding of freshwater fluxes through the Canadian Arctic Archipelago into the Labrador Sea. Results from this thesis should provide valuable information to the ASOF program in terms of synthesis and interpretation of observations and model results.

The continued research in realistic modeling of the circulation regime in the Canadian Arctic Archipelago and the rest of the Arctic will assure the U.S. Navy’s continued ability to operate in any region of the world, even under changing environmental conditions. Improving

the model’s accuracy will allow more realistic sea ice distribution and freshwater fluxes. These parameters are a good indicator of the warming in the Arctic. The extent and rate of melting of sea ice melt should be a concern to the U.S. Navy because it opens the Arctic region up to new shipping routes, especially the Northwest Passage and the Northern Sea Route, which not only has economical and environmental implications, but poses important military threats. Therefore, any information gained now, and in the near future, can only aid the U.S. Navy in its preparation to operate in a partially/seasonally ice free Arctic.

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